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Study Effect of Fluctuations of Pressure Factors of Stepped Short-throat Shaft Spillways on Hydraulic Coefficient

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Abstract

Shaft spillways are commonly used generally to empty or drain unexpected floods on earth and concrete dams. Shaft spillways are stepped or smooth. Stepped spillways discharge more flow through themselves than smooth spillways theoretically. Therefore, understanding the flow behavior of these spillways can lead to better and more efficient use. In addition, the use of a vortex breaker can have a large impact on flow through the shaft spillway. For more efficient use, the risk of flow pressure dropping below the fluid vapor pressure, known as cavitation, should be prevented as much as possible. As for the spillways with stepped conduits (three steps), the pressure changes were found to be very tangible using a sextuple arrangement of vortex breakers for intermediate discharge rates; in some of the states, the pressure on the spillway's body is found to be intensely decreased. Based on the research work, the best performance belongs to the morning glory-type spillway with 12 steps and three vortex breakers on the crest, as these accessories play an essential role in controlling the discharge rate and preventing cavitation. It is worth mentioning that the vortex breaker's dimensions based on the ratio of the vortex breaker's thickness (T) to the spillway's diameter (d) would not have an effect of more than 12.5% on the separation of the flow lines. In this study, an attempt was made to investigate the effect of different behaviors of the stepped chamber and different vortex shapes on the spillway flow. Based on the present experimental investigation, the following conclusions may be concluded: Maximum risk of flow rate is the magnitude at 1/3 downside of the shaft, and Magnitude velocity occurs at the end steps of the stepped chamber and in 1/4 of the stepped Shaft spillway. A morning–glory spillway should be placed as far as possible from reservoir boundaries to ensure radial flow over the crest. Then, the discharge calculation is straightforward, with negligible influence of the presence of piers.

1. Introduction

Demand for designing spillways dates back 3500 and the Greek were the first to design them. Water flow loses a part of its kinetic energy while passing the steps. Thus the flow velocity is decreased and aeration is increased in stepped spillways (Chanson, 2001).

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Energy loss in stepped spillways is a key factor in reducing erosion potentiality of the flow in their downstream. The stepped spillway significantly reduces energy losses from chutes. As such, they eliminate the need to build or significantly reduce energy loss systems downstream of the structure (Chanson, 2001). The flow on stepped spillways occurs in two skimming and napped regimes. In high discharges, skimming flow occurs and in low and intermediate discharges, napped flow occurs. Water flow on a stepped or unsmooth surface in earth dam spillways is completely turbulent and produces small air bubbles (Jean Pierre and Jean Pierre, 2004).

Such flow may depreciate a major part of its energy. Therefore, the more energy is lost, the less the risk of cavitation's due to intense fall of velocity. In this study, the flow capacity was measured in morning spillways considering many dimensionless parameters of Froude number at the top of spillway surface, the h/b ratio for each step and number of steps for two different types of spillway and Cd (Emptying Coefficient of Shaft Spillway) against submergence ratio (h/rs) for different vortex breaker and 3 different arrangements. To determine optimal flow conditions, the theoretical Cd versus h/rs was calculated and plotted using different guide piers and their arrangements. Finally, some factors affecting the emptying coefficient are proposed for design.

Other factors affecting vortex formation include insufficient submergence, current separation, a sudden change in the flow direction, and approaching flow field velocities exceeding 0.6 m/s (Salmasi, 2003). Investigating the numerical modeling of flows in morning glory spillways using Flow-3D, Razavi and Ahmadi (2017) found that the increased suspended load reduces the current passing through the spillway, while the dead load values were dependent on the suspended load.

The experimental results showed that the use of multidimensional spillway increases the discharge capacity and spillway discharge coefficient.

Investigating the discharge coefficient of morning glory spillways with the longitudinal angle of the vortex breaker, Musavi Jahromi et al. (2016) found that the 45-degree angle of the vortex breaker on the spillway increased the discharge coefficient. Investigating the effect of pyramidal vortex breakers on the discharge capacity of morning glory spillway, Sayadzadeh et al. (2020) found that the placement of a hexagonal group of vortex breakers caused a significant increase of approximately 51% in the discharge coefficient at the spillway crest control section and an increase of approximately 16% in the morning glory spillway.

Aim of the study:

In the recent studies, many problem has been observed through the crest of morning spillway with high flow velocity, therefore, the main of this study is about t to investigate the effect of water pressure on the morning glory spillway crest, and the way of decrease of pressure on body of steeped structure. Move over, in this study, the effect of vortex breaker on the flow regime was studied experimentally.

The main question of this research work was about the effect of vortex pressure on the hydro dynamic on the curve body of hydraulic structure, especially when the velocity is suddenly increased in critical situation.

2. Material and Methods

The flow coefficient is empirically a function of the dimensionless parameters of fluid mechanics. The flow coefficient and fluid pressure enter into the dimensional analysis calculation, which not only makes the calculation more complicated but also far from our main goal. Therefore, it is necessary to analyze the effective parameters of the flow regime and the energy loss of the step.

2.1. Dimensional analysis

Significant and effective parameters may include the velocity of flow on spillway surface (v), fluid dynamic viscosity (μ), spillway diameter (Ds), the ground gravity acceleration (g), fluid density (ρ), the width of the step (b), the height of each step (h), and the number of steps(N), S (number of Vortex Breaker) and (Cd) as discharge coefficient, Cv1 is a parameter of vortex breaker and Cv2 is parameter of stepped chamber. It is necessary to add Cv1 and Cv2 as dimensionless functions of discharge coefficient. The equation which indicates the mentioned parameters is written as below:

$$f(v, \mu, g, \rho, b, h, D_s, N, S, Cd, Cv1, Cv2) = 0 \qquad (1)$$

In accordance with Buckingham method, nine variables with three dimensions M, L and T are available. If the number of variables is deducted from the number of dimensions, the number of dimensionless equations is obtained. In this article, eight dimensionless equations are developed considering the three variables v, ρ and Ds as repeated variables:

$$\prod\nolimits_1 = (v,\rho,D_s,g) = \frac{gD_s}{v^2} = \frac{1}{Fr^2} \qquad (2)$$

$$\prod\nolimits_2 = (v,\rho,D_s,\mu) = \frac{\mu}{\rho v D_s} = \frac{1}{Re} \qquad (3)$$

$$\prod\nolimits_3 = (v,\rho,D_s,b) = \frac{b}{D_s} \qquad (4)$$

$$\prod\nolimits_4 = (v,\rho,D_s,h) = \frac{h}{D_s} \qquad (5)$$

$$\prod\nolimits_5 = (v,\rho,D_s,S) = \frac{S}{D_s} \qquad (6)$$

$$\prod\nolimits_6 = C\,d \qquad (7)$$

The first and second dimensionless equations are the reverse of Froude and Reynolds numbers, respectively. If multiplication or division of the two dimensionless equations is used, a new dimensionless equation can be made; therefore, dividing the third and the 5th dimensionless equations will be as following:

$$\prod\nolimits_7 = \prod\nolimits_4 \div \prod\nolimits_3 = \frac{h}{D_s} \div \frac{b}{D_s} = \frac{h}{b} \qquad (8)$$

$$\prod\nolimits_8 = N \qquad (9)$$

There are 5 dimensionless equations (Equations 1, 2, 4, 5, and 6). However, since the flow in spillways is free and the shear stress is very small near the surface, the effect of dynamic viscosity is very small and ignorable (μ≈0). In this case, the dimensionless equation number 2 is deleted and only the first, fifth and sixth dimensionless equations are used and analyzed. The sixth dimensionless equation indicates the number of steps. Moreover, one dimensionless parameter which are symbol of vortex and stepped chamber is defined as below:

$$\prod\nolimits_9 = \frac{Cd}{Cv1.Cv2} \qquad (10)$$

2.2. Experimental data

This study was inspired by the physical model of San Luis For eBay dam spillway, which is located at the central valley of California, America.

This model, the dimensions of which are presented in Figures 1 and 2, consists of a 2000-liter reservoir in upstream (including the body of dam, spillway and water canal), a tunnel for transferring the water from the spillway downstream, a 2000-liter reservoir in behind the water transfer tunnel and a pump for pumping water from the downstream reservoir to the upstream one. In this experimental model, the spillway body was devised in the upstream reservoir including two types of spillways with completely different designs (Figures 3, 4). The surface arc on two sides of the body of all spillways follows the same equation.

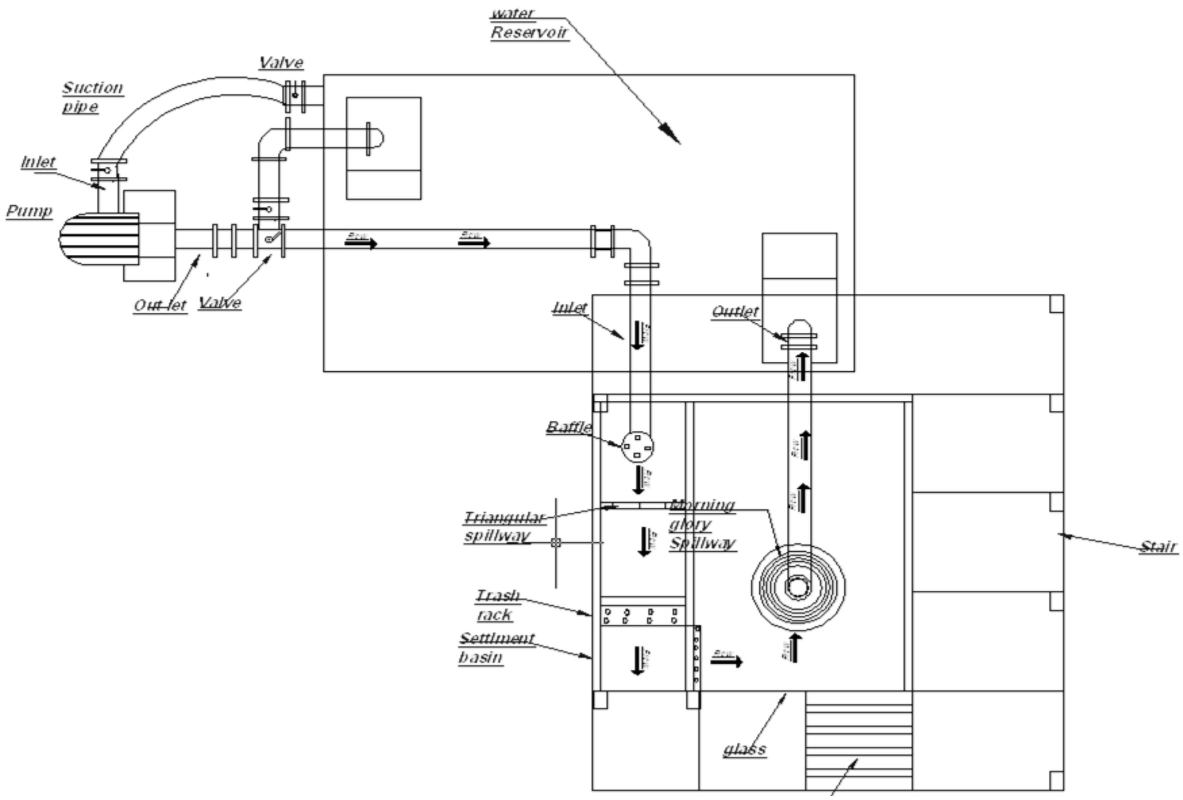

Figure 1. Upper view of the physical model (dimensions based on millimeter).

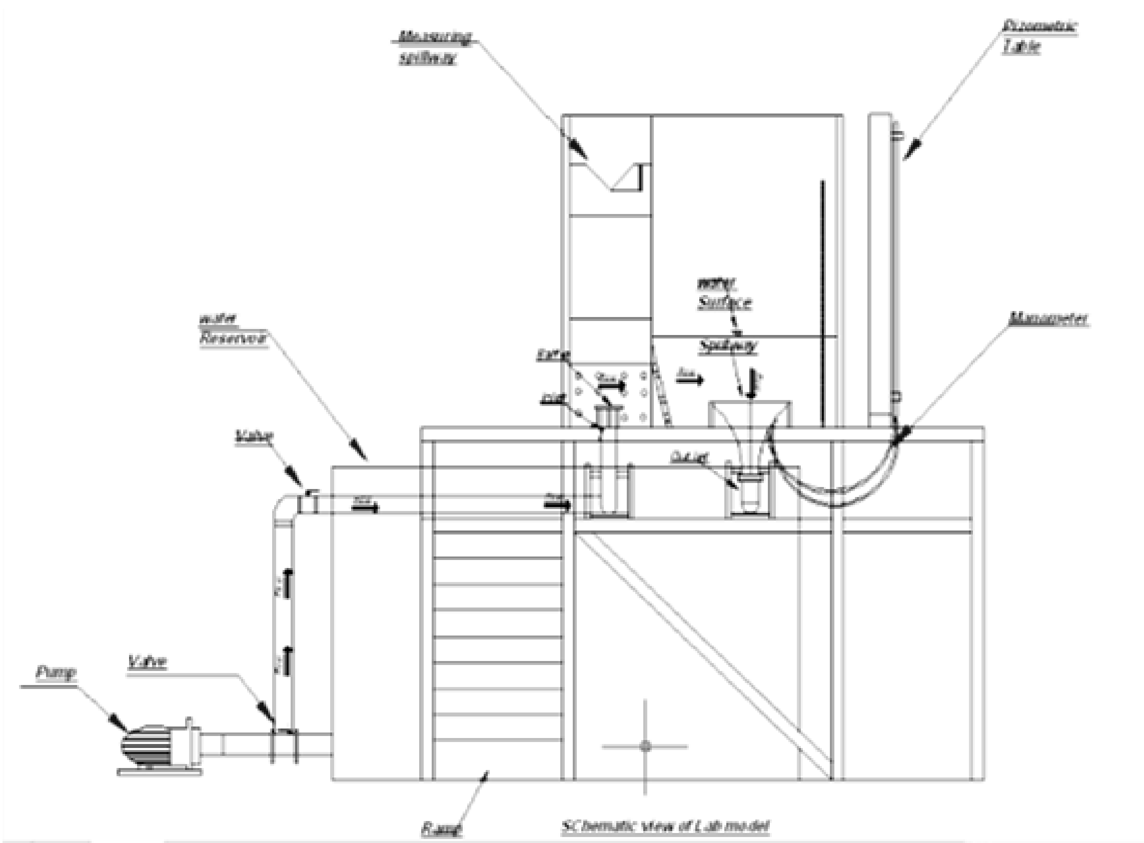

Figure 2. Cross-section of the physical model (dimensions based on millimeter).

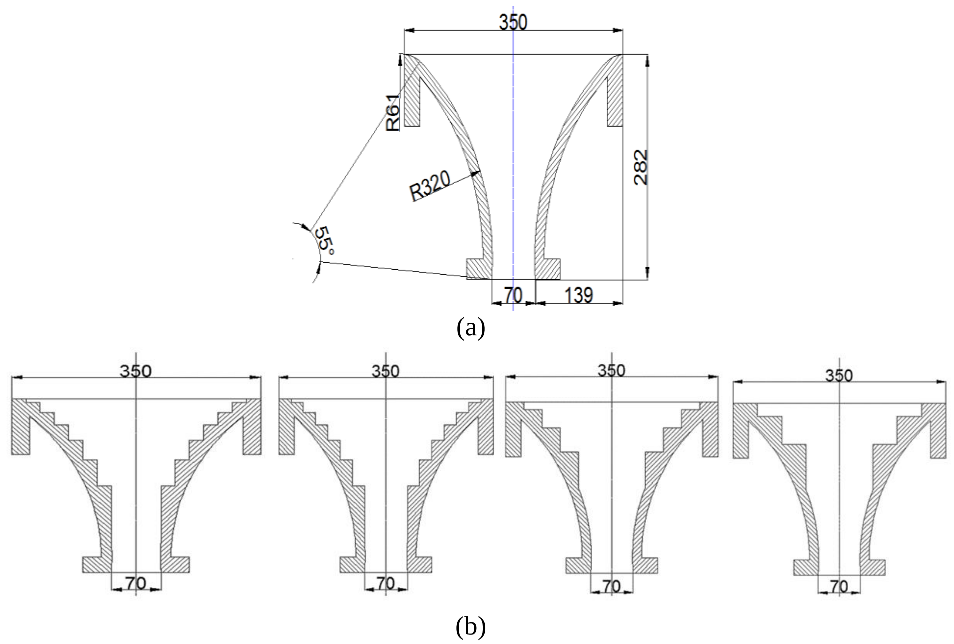

Figure 3. Physical model of shaft spillway a) smooth spillway, b) stepped spillway (dimensions of all spillways are based on millimeter).

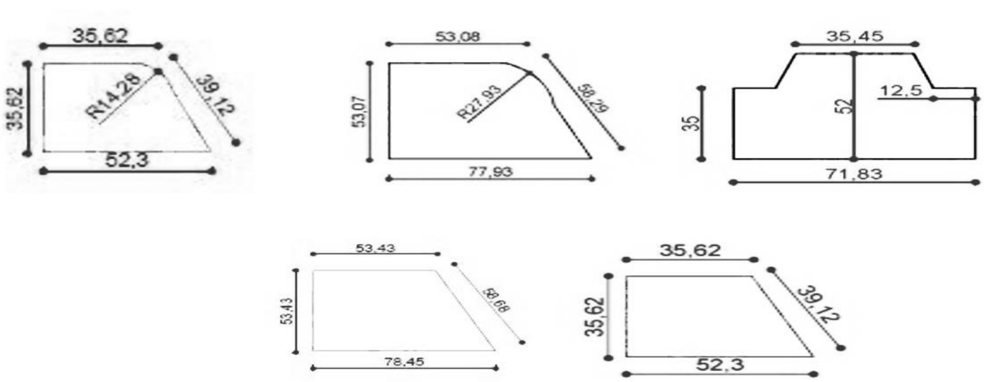

Figure 4. Different types of vortex breaker of shaft spillway.

In addition, dimensions of all spillways are the same but the internal surface of each spillway is different from the others. There are two types of spillways: those with a smooth surface those with six steps. The height and the width of step are denoted by hand b. The height and width of each step in the smooth spillway is very small and unchanging throughout. The height of each step is continuously changing in the six-step spillways, with the width of each step being two centimeters longer in each consecutive step. In the smooth six-step spillway, on a specific section there is one hole on the first step, two holes on the second, three on the third and so forth to measure water height and pressure.

In the smooth spillways, the location of the holes is the same as that of the eight holes of twelve, six, four and two-step spillways; therefore, the sum total of holes in both types of spillways is 8, 4 and 9, respectively. In this regard, the number of holes indicates the Froude number and h/b ratios required to compare the surface of the spillways with one another. It is true that all spillways should have the same number of the holes, but due to logistic difficulties, the CNC machine could not be used to make holes in the end steps; therefore, only the information related to the available points was compared (Figures 1, 2).

To determine the flow regime (Froude number) holes were made on the surface of each spillway in the spillway body at certain distances from the beginning of each spillway. The holes were used to measure water height equivalent to fluid pressure at specific points using pizo metric pipe (It is to be mentioned that Piezometer pipe is the most accurate fluid pressure measurement instrument). Afterwards, an energy equation was established between every two points on the spillway surface according to the Bernoulli principle regardless of fraction loss (Figure 3).

Assuming that the flow velocity on the first step is equal to the velocity of the flow entering the spillway, the flow velocity can be calculated from step two in the presence of a height difference equivalent to the fluid pressure. If the flow velocity at each point is specified, the Froude number related to that point can be calculated using formula 12. In addition, a triangular weir was used to measure the velocity and inlet flow discharge for each spillway:

$$\frac{v_1^2}{2g}+\frac{p_1}{\gamma}+z_1 = \frac{v_2^2}{2g}+\frac{p_2}{\gamma}+z_2+h_l \quad (11)$$

$$Fr = \frac{v^2}{\sqrt{gD}} \quad (12)$$

$$D = 4R = \frac{4A}{P} = D_s = \text{Spillway bigger diameter} \quad (13)$$

A single volume cube was used to calculate the discharge, various discharge values were checked and the Height Flow formula for a triangular weir was subtracted. The water level in the reservoir and the head on the spillway were accurately measured. Finally, other parameters were calculated. To govern vortex creation, in shaft spillways, always vortex breakers (guide pier) are located at the spillway crest, in this situation for studying the effect of different shapes of vortex breakers, 2 different shapes, and 2 different arrangements are used to estimate flow rate for two spillways (smooth and Stepped Spillways). Figure 5 shows shapes of spillways.

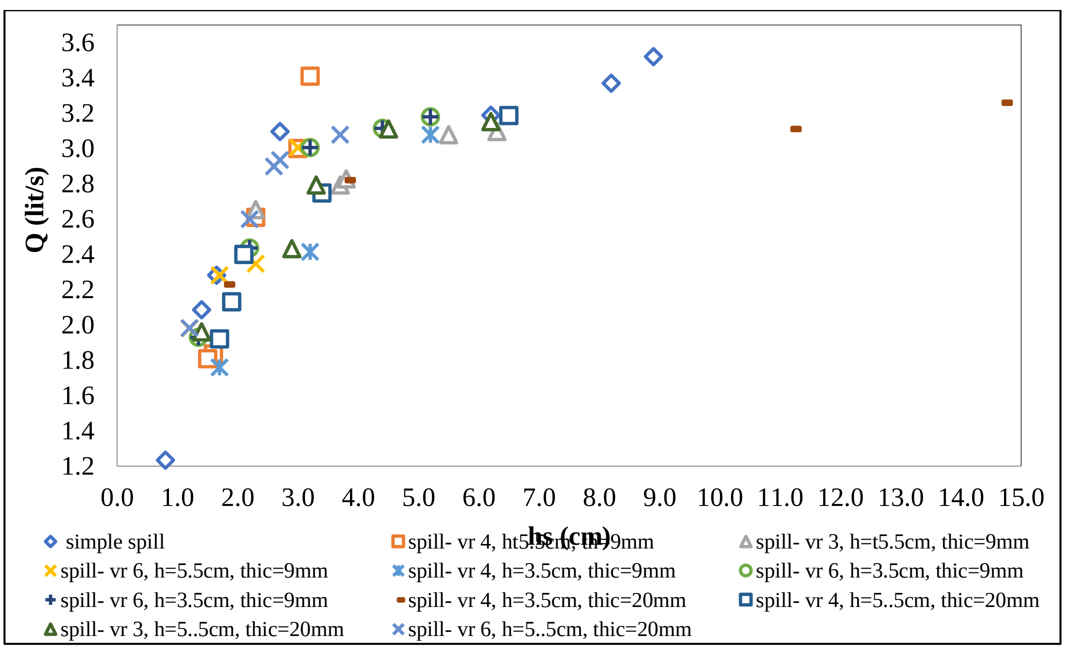

Figure 5. Discharge against head of water on crest of spillway (Smooth spillway) with different vortex breakers.

3. Results and Discussion

3.1. Hydraulic behavior of shaft stepped spillway

In the design of dams, spillways are always necessary as safety structures for conveying flood flows. Among the various types of spillways, the shaft is a rare option, which may be adopted if space is limited and other local conditions do not allow a more conventional design.

The structure normally consists of three main components, namely top cup-shaped overflow inlet, the vertical shaft, and a nearly horizontal conduit leading to a dissipation structure.

Ideally, the flow over the crest and into the shaft should have a free surface. Then considering symmetric radial inflow over the circular crest of radius R, the stage–discharge relationship is similar to that of a straight–crested spillway, substituting the circumference of the cycle, 2πR, for the length L. According to Shuguang (2002), the discharge is given as:

$$Q = Cd\ 2\pi R\ h^{1.5} \sqrt{2g} \qquad (14)$$

Some experiments were carried out to evaluate the different emptying ratios of the shaft spillway, as shown in Table 1.

Table 1. Information of experiment.

Type of spillway	Different discharge	Type of vortex breaker	arrangement	Thickness of vortex breaker	Number of experiments
4	5	5	3	2	600

To create a wide range of information, various discharge values were used from Q = 1.13 l/s to Q = 6 l/s. Equation (14) was used to determine the flow coefficient. As a result, it was found that the best schedule and optimal Cd for a smooth spillway was associated with the use of the vortex breaker number 6 as the location, and the best vortex breaker was number 3 in Figure 4. These results are shown in Figures 6-10.

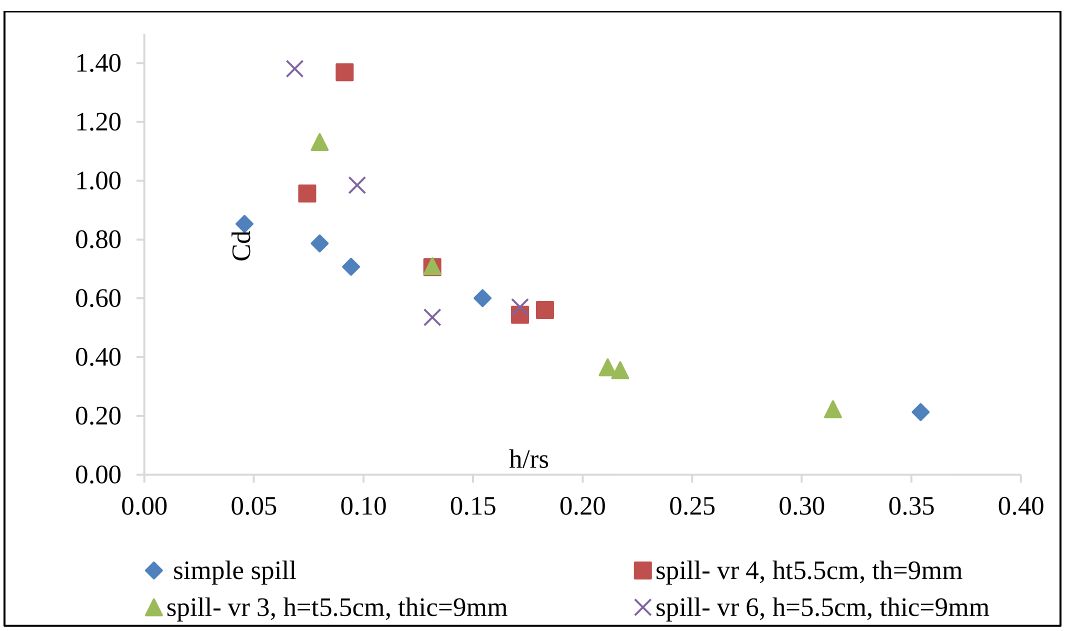

Figure 6. cd against h/rs (smooth spillway) with low height v. breaker.

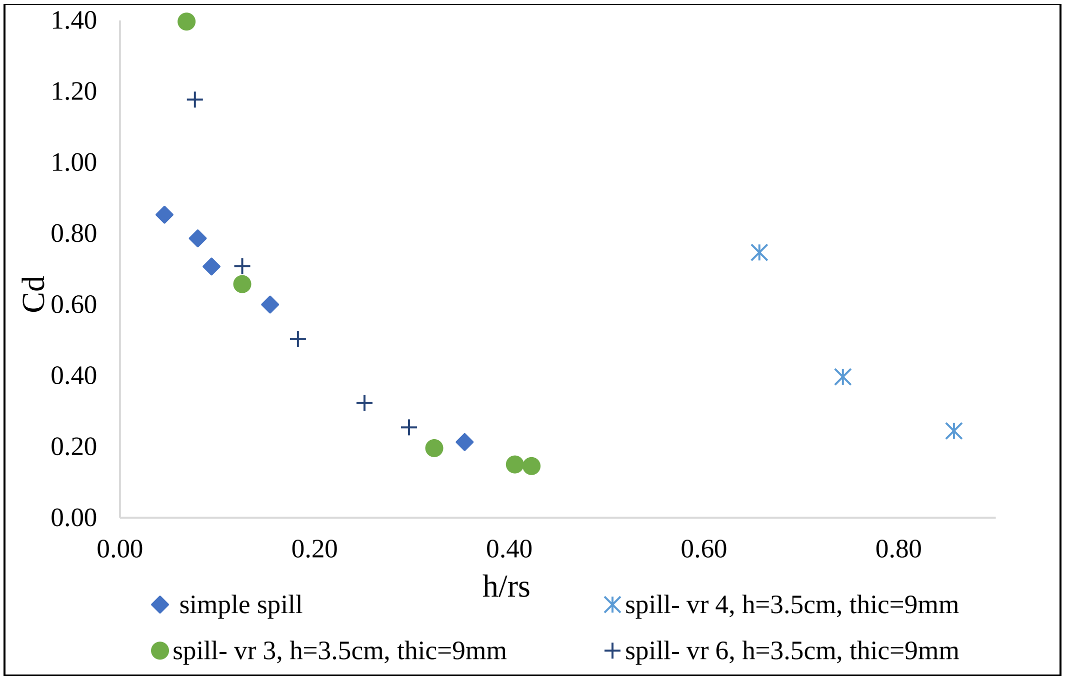

Figure 7. cd against h/rs (smooth spillway) with low height v. breaker.

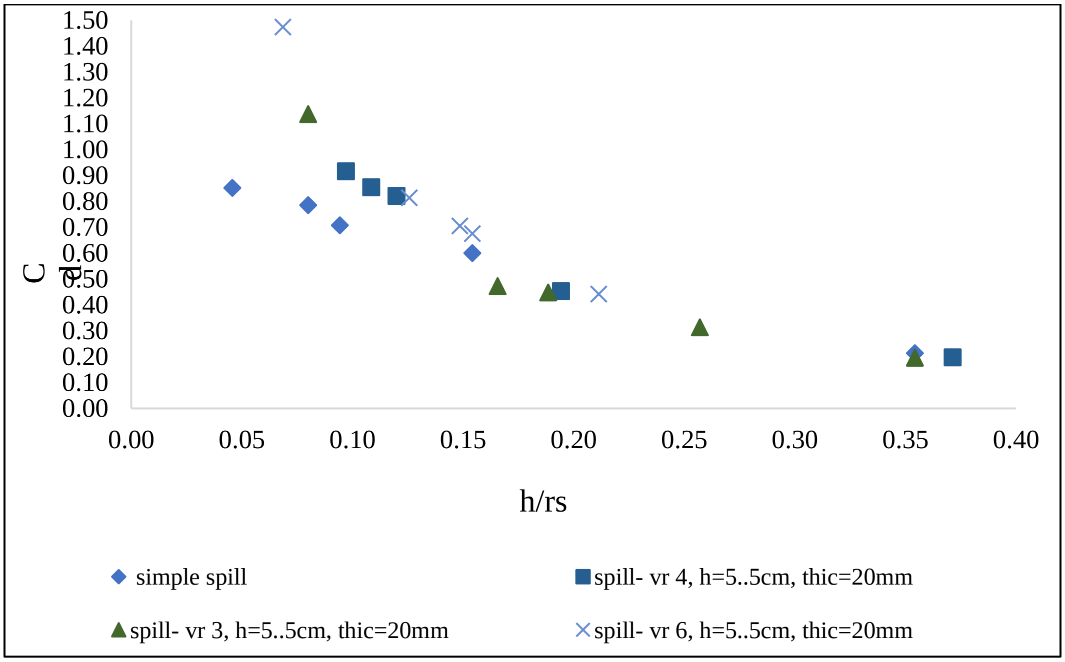

Figure 8. Cd against h/rs (smooth spillway) with low medium v. breaker.

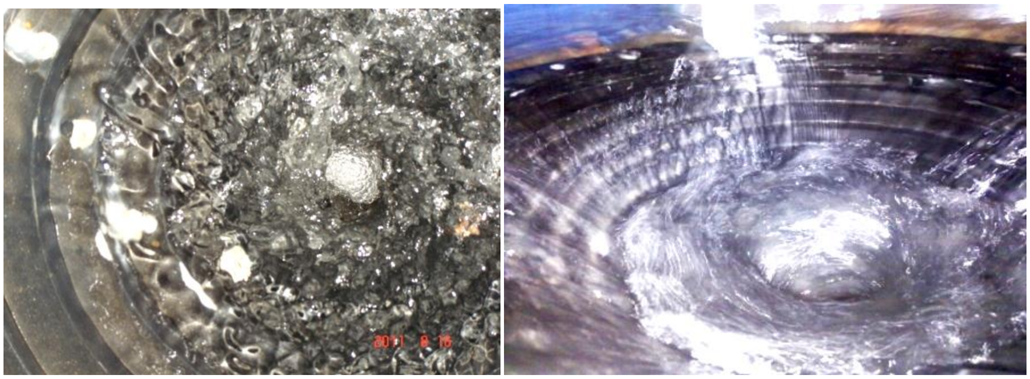

Figure 9. Experiment with three vortex breaker shaft spillways.

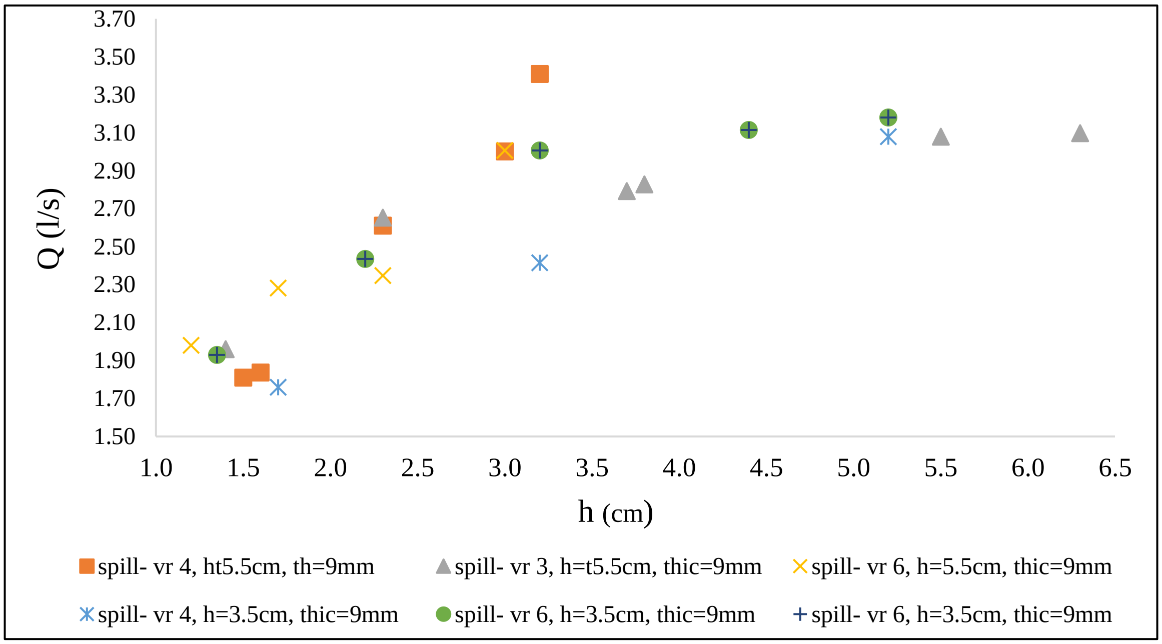

Figure 10. Discharge against head of water on crest of spillway (stepped spillway) with different vortex breaker.

According to Figure 9, the best discharge coefficient is related to 6 vortex breakers as arrangement and the flow rate increase more than 15% on average. Nonetheless, height increase of vortex breaker has a limited influence on flow rate increase. Moreover, when vortex passes through spillway body, vortex breaking has a small impact on the control of flow rate, and as long as the spillway is completely submerged, vortex control function does not continue. Moreover, when the thickness of vortex breaker is bigger than 0.2Rs, the emptying coefficient is not effective, especially when a spillway with 4 vortex breakers is used.

To compare the two spillways, all experiments were repeated. Figure 10 show the results for a stepped morning spillway compared to six-step spillways.

As a result, it was revealed that the optimum discharge coefficient was related to six Vortex breakers series, in which the flow rate increased more than 13 %on average. Nonetheless, the increase in the thickness of the vortex breaker has a limited effect on the increase in flow. Moreover, when the vortex is generated through the body of the spillway, the fall of the vortex has a limited impact on controlling the flow rate, while the spillway is completely submerged due to differences of flow regime in stepped shaft spillways. In some cases, a vortex breaker decreases the flow rate of discharge (Figure 11).

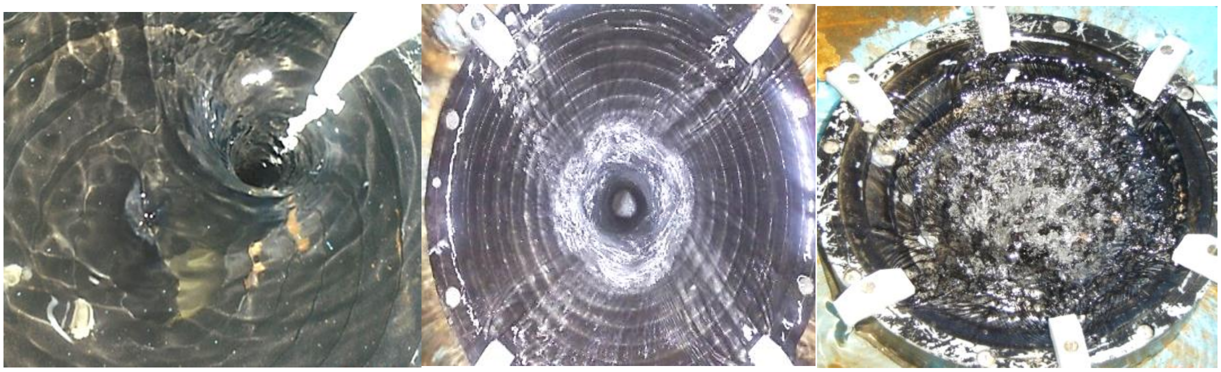

Figure 11. Flow passing through stepped spillway (stepped spillway) with creation vortex at down side of spillway.

When the two spillways were compared, it was found that a fully stepped chamber significantly increased the flow rate.

According to Figure 12, the stepped shaft spillway had the best flow rate, as the flow rate increased as much as 12% on average. To better understand the effect of the stepped chamber on the flow characteristics, some mathematical equations were developed for the spillway with a smooth and stepped shaft using the SPSS software, using Equation (2).

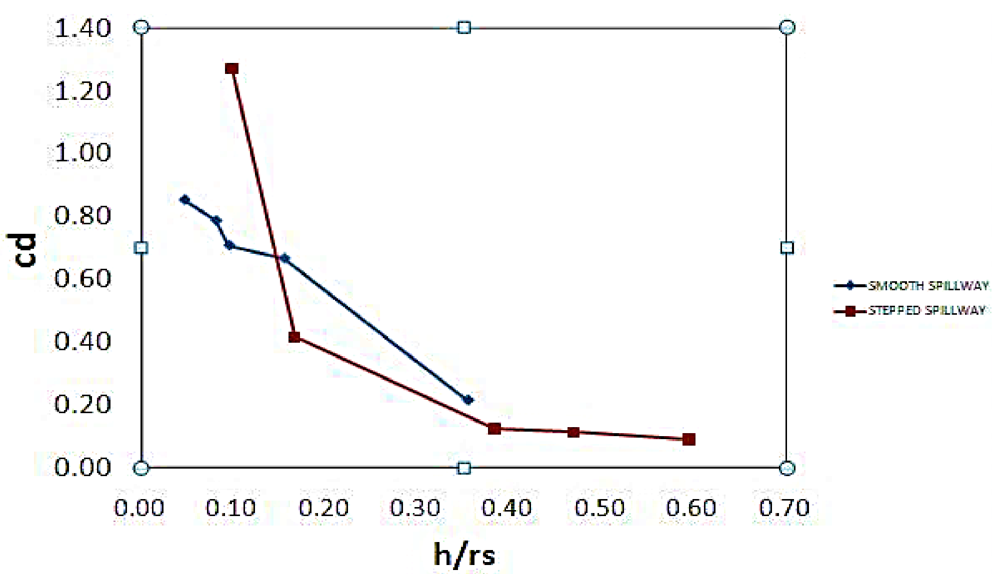

Figure 12. Cd against h/rs (stepped spillway) and smooth spillway without vortex breaker.

For a smooth spillway, this equation looks like this:

$$Cd = 1.725 \times \left(\frac{H}{rs}\right)^{-0.133} \times 0.147 \times (Fr)^{-1.38} \qquad (15)$$

For stepped spillway, the equation is as below:

$$Cd = 0.016 \times \left(\frac{H}{rs}\right)^{-1.629} \times 1.949 \times (Fr)^{0.364} \qquad (16)$$

These equations show that effect of stepped chamber on emptying coefficient is significant. Thus, some useful equations can be developed for designing more efficient spillways.

Various experiments were carried out to study the effect of different shapes of the vortex breaker and different locations of the guide pier on the crest of the spillway. According to these experiments, the best efficiency of the flow coefficient is associated with the shape of the ogee in the form of a vortex breaker with the six steps on the crest. Table 2 shows the results of various flow rates.

According to Table 2, the best result of using a vortex breaker is associated with an ogee-shaped breaker, which has a better effect on the passage of streamlines through the spillway. In other words, minimal eddies will occur when the streamline moves smoothly near the body of the shaft spillway, as re result of which one boundary line with less friction will appear.

Table 2. Effect of vortex breaker on increasing discharge coefficient (with using 6 vortex breaker).

Shape of vortex breaker	Cd	h/rs	Q (L/s)	Shape of spillway	Efficiency increasing rate
Without vortex breaker	0.41	0.09	2.25	smooth	1
Triangular long	0.81	0.092	2.26	stepped	1.18
Triangular short	0.44	0.172	2.26	stepped	1.07
Triangular middle	0.62	0.141	2.27	stepped	1.14
ogee shape	0.69	0.12	2.26	stepped	1.22
rectangular	0.605	0.096	2.26	stepped	1.09

For a better understanding and applicability of experiments in accordance with the number (10), some coefficients were developed, presented in Table 3.

Table 3. Effect of vortex breaker on increasing discharge coefficient (with using 6 vortex breaker) and coefficients of steps and vortex breaker.

Cv1	Cv2	l_c/d	t_v/d	l_v/d	n_v/d	Cd	h/r_S	Discharge (lit/s)
1	1	0	0	0	0	0.87	0.08	2
1	1.62	0	0.025	0.2	6	1.38	0.073	1.98
0.69	1	0	0	0	0	0.59	0.17	2.03
0.28	1.62	0.06	0.025	0.2	3	0.63	0.13	1.97
0.929	1	0.086	0	0	0	0.79	0.08	2.05
0.543	1.32	0.086	0.025	0.2	3	0.81	0.079	2.04
0.81	1	0.11	0	0	0	0.69	0.102	2.05
0.449	1.32	0.11	0.025	0.2	3	0.67	0.12	2.06
1.02	1	0.028	0	0	0	0.86	0.08	2.01
0.398	1.62	0.028	0.025	0.2	6	0.86	0.098	2.03

In this table, Lc is the number of steps in spillway barrel, Tv is the thickness of the vortex breaker, Lv is the length of the vortex breaker, d is the structure diameter, and h/rs is the submergence ratio.

According to Table 3, the best discharge coefficient is related to a smooth spillway with 6 vortex breakers (Cd = 1.38) followed by stepped spillways with 12 steps and 6 vortex breakers.

As a result, it was found that when using a stepped chamber, the emptying parameter is reduced by an average of about 30%, and when using a vortex breaker with six arrangements and an ogee-shaped shape, suitable conditions were created for the passage of the flow. In other words, a stepped chamber has a very good performance, especially when the risk of cavitation has to be taken into account.

As for vortex breakers, equations were developed to calculate Cd based on submerged rations. These formulas were calculated for a 12-step spillway with different vortex breakers (Table 4).

Table 4. Design formula for stepped morning spillway.

No	Equations	Descriptions
1	$Cd = 0.073*\left(\frac{h}{rs}\right)^{-1.218}$	Cd for spillway with 4th Vortex breaker (with ogee shape)
2	$Cd = 0.0578*\left(\frac{h}{rs}\right)^{-1.125}$	Cd for spillway with 3 Vortex breakers (with ogee shape)
3	$Cd = 0.0278*\left(\frac{h}{rs}\right)^{-1.678}$	Cd for spillway with 6 Vortex breaker (with ogee shape)

3.2. Investigation pressure on body of spillway

One of the most important issues with spillway hydraulics has to do with pressure changes from the top of the spillway to the barrel. In other words, when the flow changes and moves up until the full pipe state, the pressure will change and fluctuate greatly, and when the crest control point is transferred to the orifice monitoring state, there will be some vibration in the lower part of the spillway, and a negative pressure area will appear. Corrosion can damage the concrete surfaces in the spillway.

According to the study, when flow rises to near unsustainable submergence zone, the maximum negative pressure appears, leading to the crisis situation for cavitation is this condition. This is quite different for every spillway with a stepped chamber and a different vortex breaker on Based on this experiment, while the flow changes from crest control to orifice zone, critical changes may happen. Table 5 illustrates the dangerous zone of different spillways with various conditions.

Table 5. Limitation of cavitation's risk *vs.* submergence ratio.

No	Spillway type	Vortex breaker arrangement	Minimum H/re ratio for cavitation risk probability	Maximum H/re ratio for cavitation risk probability
1	smooth	6 vortex breaker on crest	More than 0.45	Less than 0.37
2	6 STEPS	6 vortex breaker on crest	More than 0.38	Less than 0.34
3	4 STEPS	6 vortex breaker on crest	More than 0.36	Less than 0.28

4. Conclusions

Based on the present experimental investigation, the following conclusions may be drawn:

a. Maximum risk of flow rate is magnitude at 1/3 down side of shaft.

b. Magnitude velocity occurs at the end steps of the stepped chamber and in 1/4 of the stepped shaft spillway.

c. Depending on the simulation, the height and the width of each step on the stepped chamber have great effect on flow regime, especially when the flow regime changes from nape to skimming flow.

d. A morning – glory spillway should be placed as far as possible from reservoir boundaries to ensure radial flow over the crest. Then, the discharge calculation is straight forward, with negligible influence of the presence of piers. Boundary proximity may induce vortex flow and significantly reduce the capacity of the spillway. Therefore, if vortex development is anticipated, a larger structure (inlet/ shaft/ outlet conduit) would be needed, implying Higher construction costs.

e. Placement of piers on the crest is an efficient way of coping with the negative effects of the vortex. The significance of piers is evident mainly for high discharges, as they can limit the stage increase to about half the value observed without piers, and also suppresses water level oscillations. Stepped shaft spillways have an effect on flow rate and in some cases, which may cause flow rate to increase. Stepped chamber may be associated with cavitation risk.

f. According to the experiments, although the stepped chamber on the spillway reduces the flow rate and the risk of cavitation, an ogee-shaped vortex breaker increases the flow rate as much as 22%.

Data Availability

The data used to support the findings of this study is available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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Author Contributions

Design and construction of models, data collection, and statistical analysis, the share of the first author is 70%, and the second author's share is 30% of the total.

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