



Study of Pressure Variation with Discharge Coefficient on the Stepped Short Throat Shaft Spillway by Considering Vortex Breaker

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ABSTRACT

Shaft spillways are Spillways used generally for emptying and evacuating unexpected floods on earth and concrete dams. There are different types of Shaftspillways: Stepped and Smooth ones. These spillways (Stepped spillways) pass more flow discharges through themselves in comparison to smooth spillways theoretically. Therefore, awareness of flow behavior of these Spillways, help using better and more efficiently. Moreover, using vortex breaker has great effect on passing Flow through Shaft Spillway. For using more efficiently, the risk of flow pressure decreases to less than fluid vapor pressure, called cavitations, should be prevented as far as possible. At this research, it has been tried to study Different behavior of Stepped chamber and different vortex shapes on spillway flow. From the viewpoint of the effects of flow regime changes on spillway, changes of step dimensions, and the change of type of Discharge will Studied Effectively. And finally the best the relation between pressure and Discharge Coefficient are determined.

Key words: Shaft Spillway, Flow, Steps, Submersible ratio, Discharge Coefficient.

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INTRODUCTION

Designing Spillway goes back to 3500 years ago, and the Greek were the first people who designed them. Water flow loses a part of its kinetic energy while passing the steps, and as a result, the flow velocity is decreased and aeration is increased in this Type of spillway (Chanson, H, 2001).

Energy loss in stepped spillways is a key factor for minimizing erosion potentiality of the flow in their downstream. The step spillways can significantly decrease the energy loss resulted from chute and eliminate the need to establishment of energy loss system in structure's downstream or decrease it significantly (Chanson, H, 2001). The flow on stepped spillways occurs in two skimming and napped Regime. In high discharges, skimming flow will appeared and in low and intermediate discharges napped flow would occur.

Water flow on a stepped or unsmooth surface in earth dam spillways is completely turbulent and makes small bubbles (Jean-Pierre, F. And Jean Pierre, M, 2004).

Such flow may depreciate a major part of its energy. Therefore, the more is the lost energy the less is the risk of cavitations due to intense fall of velocity. In this study, the Flow Capacity and the is measured in morning spillways in regard to many dimensionless parameters of Froude number, at top of spillway surface, the h/b ratio for each step and number of steps for two different types of spillway, and finally, Cd (Emptying Coefficient of Shaft Spillway) against Submersible ratio (H/Rs) for different vortex breaker and 3 different arrangement were studied. For determination the best

condition of flow, with using different guide pier and its arrangement, Cd against h/rs are Calculated and plotted theoretically. Eventually, some factors which are influenced on emptying Coefficient are present for designing. (Falvey, H.T., 1990)

Discharge Evaluation

Discharge Coefficient and is empirically a function of Fluid Mechanic dimensionless parameters. Where Discharge Coefficient, fluid pressure enters dimensional analysis calculations, not only they make the results more complicated but also bring far from our main objective (Hazzab, A. And C. Chafi, 2006). Therefore, the parameters effective in flow regime and energy loss of the step are to be analyzed.

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), step width (b), height of each step (h), and number of steps (N), S (number of Vortex Breaker) and (Cd) as Discharge Coefficient, Cv1 is related parameter of vortex breaker and Cv2 is parameter of Stepped chamber It is need to add Cv1 and Cv2 are Dimension less functions of Discharge coefficient. The equation which indicates the mentioned parameters is written as below:

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

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 would be achieved. In this

article, eight dimensionless equations are developed considering the three variables v , ρ and D_s as repeated variable:

$$\Pi_1 = (v, \rho, D_s, g) = \frac{gD_s}{v^2} = \frac{1}{Fr^2} \quad (2)$$

$$\Pi_2 = (v, \rho, D_s, \mu) = \frac{\mu}{\rho v D_s} = \frac{1}{Re} \quad (3)$$

$$\Pi_3 = (v, \rho, D_s, b) = \frac{b}{D_s} \quad (4)$$

$$\Pi_4 = (v, \rho, D_s, h) = \frac{h}{D_s} \quad (5)$$

$$\Pi_5 = (v, \rho, D_s, S) = \frac{S}{D_s} \quad (6)$$

$$\Pi_6 = C_d \quad (7)$$

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

$$\Pi_7 = \Pi_4 \div \Pi_3 = \frac{h}{D_s} \div \frac{b}{D_s} = \frac{h}{b} \quad (8)$$

$$\Pi_8 = N \quad (9)$$

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 surface, the effect of dynamic viscosity is very little and ignorable ($\mu \approx 0$). 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 indicated the number of steps. Moreover, one Dimensionless Parameter which are symbol of vortex and stepped chamber is define as below:

$$\Pi_9 = \frac{C_d}{C_{v1}C_{v2}} \quad (10)$$

MATERIALS AND METHODS

This study has been 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 have been presented in figure (1, 2), is constituted of a 2000-liter reservoir in upstream (including the body of dam, spillway and water canal), a tunnel for transferring the spillway's water to downstream, a 2000-liter reservoir in downstream of the water transfer tunnel and a pump for water suction from the downstream reservoir to the upstream one. In this experimental model, the spillway body including two types of spillways with completely different designs is devised in the upstream reservoir (figures 3 to 4). The surface arc on two sides of the body of all spillways follows a same equation.

Besides, dimensions of all spillways are the same but the internal surface of each spillway is different from the other. The first type spillway has a smooth surface, and the spillways of the second type respectively have 6-step. The height of each step is h and the width of each step is b . For the smooth spillway it has been supposed that the height and width of each step is very small and same to each other. For the spillways of the second type, the height of each step is continuously changing, and width of each step is fixed and respectively equal to, two centimeters for each spillway. In the Smooth, six-step spillways, one, two and

more holes are made respectively on a specific section on each step for calculating water height equivalent to pressure.

In smooth spillway, location of holes is considered the same as that of the 8 holes of twelve, six, four and two-step spillways; therefore, the sum total of holes in spillways of type one to two is respectively 8, 4 and 9. In this regard, Number of holes indicates the Froude number and h/b ratios we require in order to compare the spillways' surfaces with each other. It is true that the number of holes in all spillways should be equal to each other, but due to long distance of the route, the CNC machine cannot make holes in the ending steps; therefore, only the information related to the available points are compared with each other.

Figure 1: Upper view of the physical model (Dimensions based on millimeter)

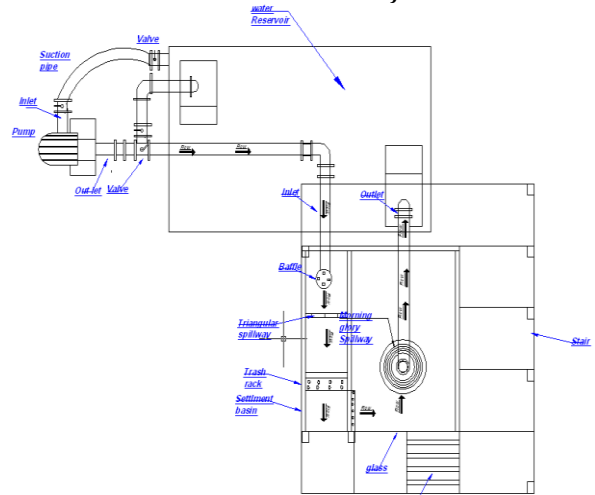
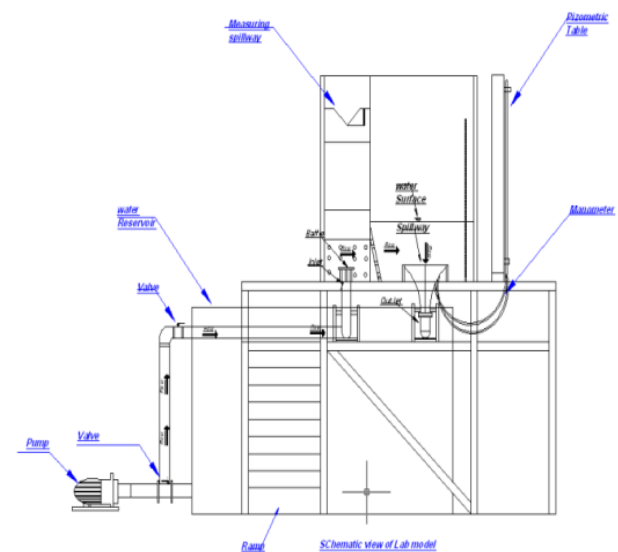


Figure 2: Cross section of the physical model (dimensions based on millimeter)



To determine the flow regime (Froude number) at surface of each spillway some holes are made in the spillway body with specific distances from the beginning of each spillway. The role of each hole is to measure the water height equivalent to fluid pressure at that specific point using Pizometric pipe. (It is to be

mentioned that Piezometer pipe is the most accurate fluid pressure measurement instrument). Afterwards, energy equation is established between every two points on spillway surface according to Bernoulli principle regardless of fraction loss.

Figure 3: Physical model of smooth and six-step spillway

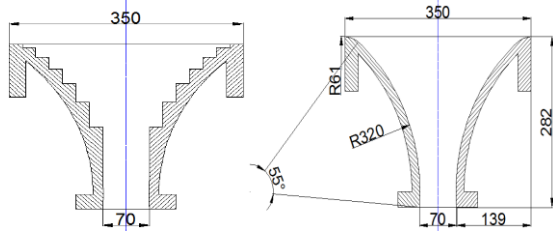
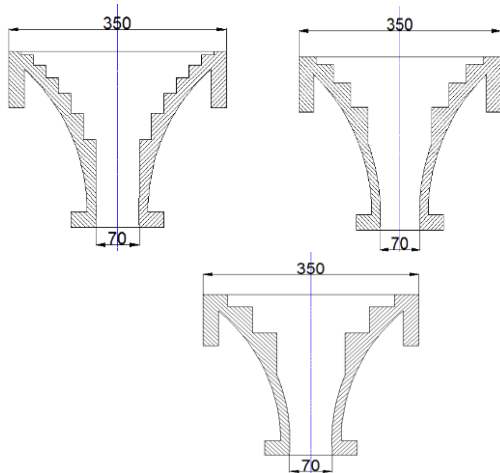


Figure 4: Physical model of other stepped shaft spillway



(Dimensions of all spillways are based on millimeter)

Supposing 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 on having available the difference of height equivalent to fluid pressure. If the flow velocity at each point is specified, the Froude number related to that point can be calculated using formula 12. Besides, to measure the velocity and inlet flow discharge for each spillway, Triangular weir has been used:

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

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

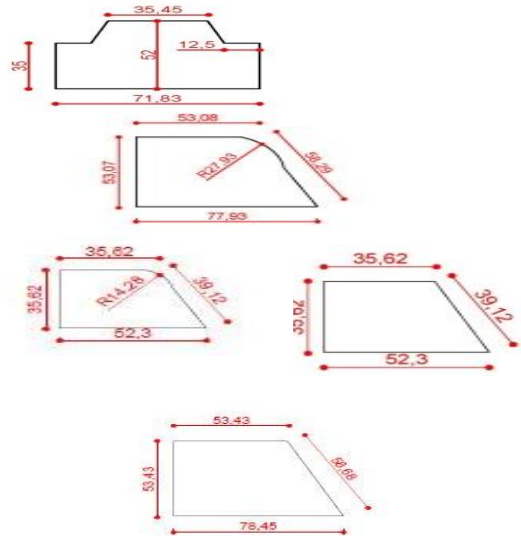
$$D = 4R = \frac{4A}{P} = D_s = \text{Spillway bigger diameter} \quad (13)$$

In order to calculate flow rate, one volumetric cube is used and different flow rate was validate and Height - Discharge formula for Triangular weir was deducted. Water level of Reservoir and head on spillway was measured accurately. Finally different parameter s is calculated.

To govern Vortex creation, in Shaft spillways, always vortex breakers (guide pier) are located at spillway crest, in this situation for studying effect of different shape of vortex breaker, 2 different shape, and 2 different arrangement are used to

estimate flow rate for two spillways (smooth and Stepped Spillways). The figure (5) shows shapes of spillways.

Figure 5: Different types of vortex breaker of Shaft spillway



DISCUSSION AND CONCLUSION

(Hydraulic behavior of Shaft Stepped Spillway: In the design of dams, spillways are always necessary as safety structures for conveying flood flows (Egemen A. And B. Mehmet, 2009). 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. The 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. Indeed, according to Vischer and Hager (1998), the discharge is given as:

$$Q = Cd2\pi Rh^{1.5} \sqrt{2g} \quad (14)$$

In this section for estimation Different Emptying Coefficient of Shaft spillway, some experiments were run as below:

Table 1: Information of experiment which been done

Type of spillway	Different discharge	Type of vortex breaker	arrangement	Thicknes of vortex breaker	Number of Experiments
4	5	5	3	2	600

For creation wide variety of information different discharge from Q= 1.13 lit/s to Q= 6 lit/s were used. And for determination of Discharge Coefficient, equation (14) is used ideally. As a result, It was revealed that best graph and optimum Cd for smooth Spillway is related to utilize vortex breaker with 6 number as arrangement, and the best vortex breaker is number 3 in figure (5). Figure (8) to Figure (11) shows these results.

Figure 6: Discharge against Head of water on crest of Spillway (Smooth spillway) with different Vortex Breaker

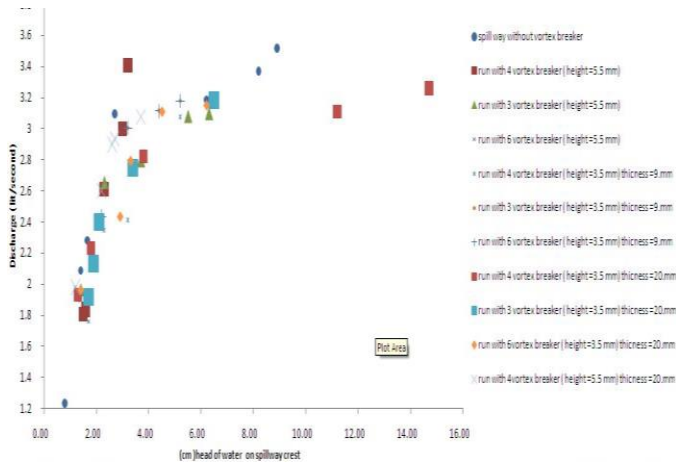


Figure 7: Cd against h/rs (Smooth spillway) with low height v. breaker

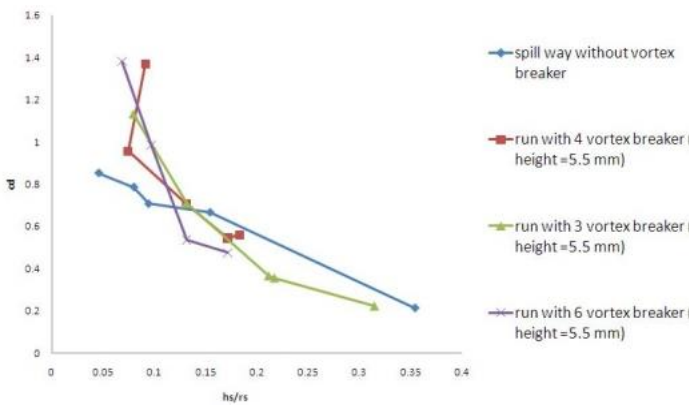


Figure 8: Cd against h/rs (Smooth spillway) with low height v. breaker

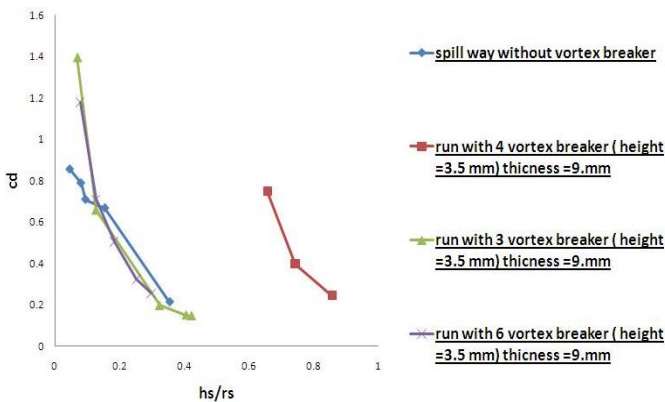
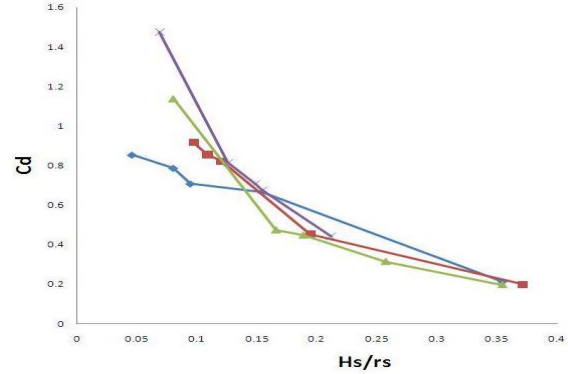


Figure 9: Cd against h/rs (Smooth spillway) with low medium v. breaker



According to figure (9) the best Discharge Coefficient is related to 6 Vortex breakers as Arrangement and the flow rate increase more than 15 % averagely. But it should be add, that height increase of vortex breaker has limitation to influence on flow rate increase. In the other hand, when vortex will appeared through Spillway body, Vortex breaking has limitation to control flow rate and while spill way is completely submerged, the function of vortex controlling is not continued. Moreover, when the thickness of Vortex breaker is bigger than 0.2Rs, the emptying Coefficient is not effective, especially when spillway with 4 Vortex breaker will used.

Picture(1): Experiment with three vortex breaker shaft spillway



When Stepped Morning Spillway are used the results are completely different, For comparison between two Spillway, all Experiment were Run again, Figure (10) to (13) show the results of runs with Stepped morning Spillway with 6 Steppes.

Figure10: Discharge against Head of water on crest of Spillway (Stepped spillway) with different Vortex Breaker

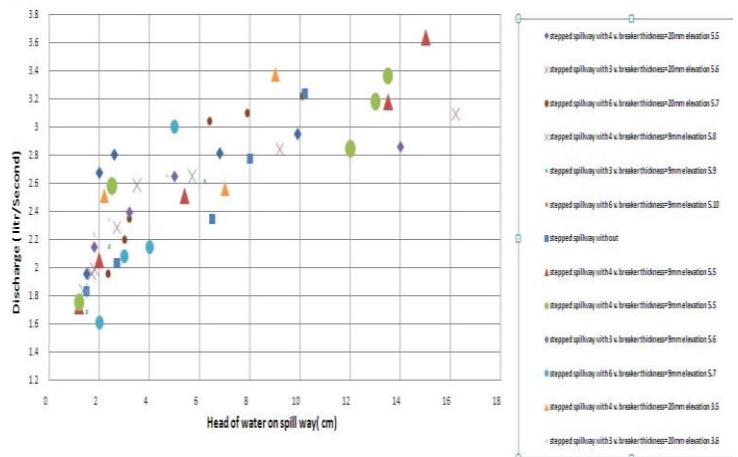


Figure 11: Cd against h/rs (stepped spillway) high height v. breaker thickness 20mm

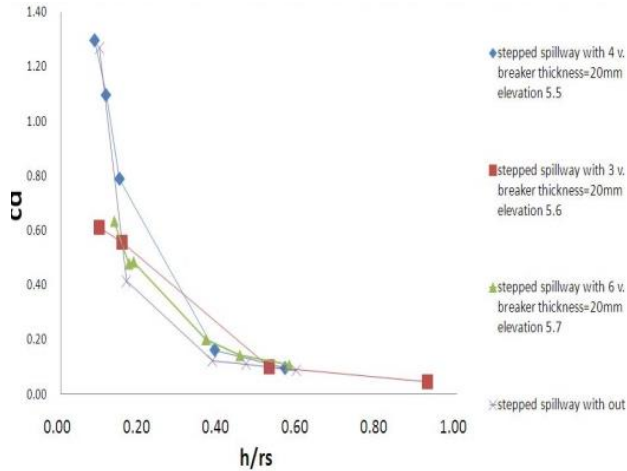


Figure 12: Cd against h/rs (Smooth spillway) with low height v. breaker thickness 9 mm

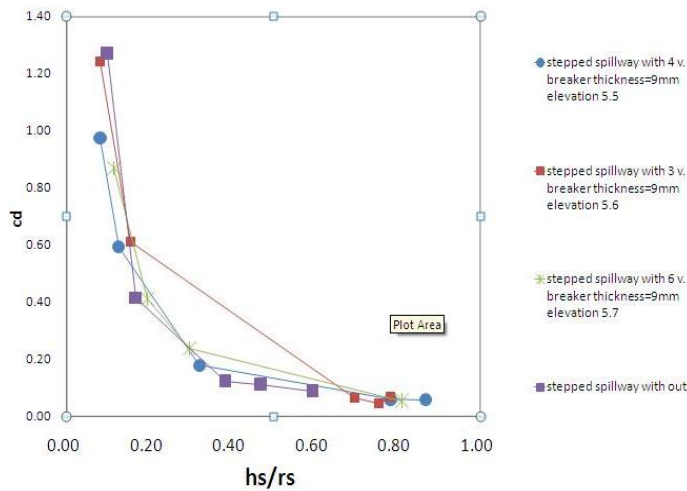
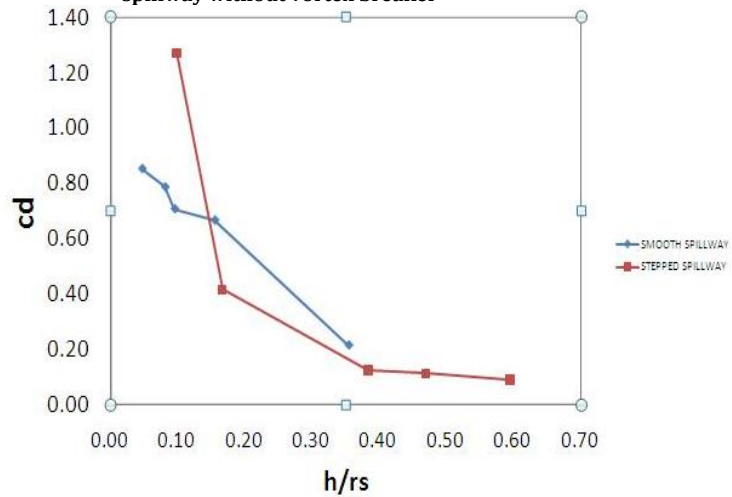


Figure13: Cd against h/rs (stepped spillway) and smooth spillway without vortex breaker



According to figure (15), the stepped Shaft spillway has better flow rate range and subsequently it is revealed that flow rate ,at this situation, increase 12 % averagely. For better understanding Effect of Stepped chamber on flow characteristics, some mathematical equation has been developed for smooth and stepped Shaft spillway by using S.P.S.S software as following: (Its need to add for this section equation (2) has developed). For Smooth spillway this equation is as below:

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

For stepped spillway the equation is as below:

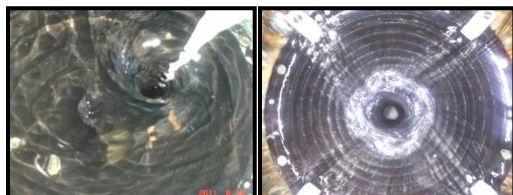
$$Cd = 0.016 * \left(\frac{H}{rs}\right)^{-1.629} * 1.949(Fr)^{0.364} \quad (16)$$

These equations show that effect of stepped chamber on Emptying Coefficient is significant and some useful equation can be developed for designing more efficient spillway. For studying effect of different shapes of vortex breaker and different arrangement of guide pier on crest of spillway, some different experiments were done. According to these runs, the best efficiency of discharge coefficient is related to ogee shape as vortex breaker with sixth number on crest. Table (2) shows the result of different discharge coefficient:

Table (2): Effect of vortex breaker on increasing Discharge Coefficient (with Using 6 vortex breaker)

As a result, it is revealed that the optimum Discharge Coefficient is related to 6 Vortex breakers series and the flow rate increase more than 13 % averagely. But it should be add, that Thickness increase of vortex breaker has limitation to influence on flow rate increase. In the other hand, when vortex will appeared through Spillway body, Vortex breaking has limitation to control flow rate and while spill way is completely submerged. This phenomenon is because of difference of flow regime, which appeared at Stepped Shaft Spillway. In some cases, using vortex breaker decrease flow rate of discharge (Figure (15)).

Picture (2): Flow passing through Stepped spillway (stepped spillway)



Picture (3): Flow passing through Stepped spillway (stepped spillway) with creation vortex at down side of spillway

Shape of vortex breaker	Cd	H / R _s	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

Due to table (2), the best result of utilizing vortex breaker is related to ogee shape vortex breaker which has better effect on passing stream lines through spillway. In the other words, minimum eddies will occur when stream line move smoothly near Shaft spillway body and one boundary line with lower friction will appeared subsequently.

For better understanding and applicability of Experiments, According to number (10), some coefficient were developed which are present as table (3).

Table (3): Effect of vortex breaker on increasing Discharge Coefficient (with Using 6 vortex breaker) and coefficients of steps& vortex breaker

C ₃	C _T	l _c /d	t _v /a	l _v /a	n/a	Cd	H/R _s	Q(L/s)
1	1	0	0	0	0	0.87	0.08	2
1	1.62	0	0.025	0.2	6	1.38	.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	0.89	0.098	2.03

In this table L_c is number of steps in spillway barrel, T_v is thickness of vortex breaker, L_v is length of vortex breaker, d is structure diameter and H/R_s is submersible ratio.

According to table (3), the best discharge coefficient is related to smooth spillway with 6 vortex breaker (Cd= 1.38) and second better Cd is stepped spillway, with 12 steps, and 6 vortex breaker.

As a result, It is revealed that when steps chamber will be used emptying parameter decrease averagely about 30 % , but when vortex breaker with 6 arrangement and ogee shape will be utilized , suitable condition for passing flow will be appeared. In the other words, using steps chamber has very good efficiency, especially when cavitations risk should be considered

In order to use these result for using vortex breaker, some equation for calculating Cd based on Submersible ration have been developed. These formulas are estimate for twelve steps spillway with different vortex breaker:

Table (4): Design formula for Stepped morning spillway

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

Investigation Pressure on body of Spillway:

One of the most important issues on hydraulic of spillway is related to Pressure variation on crest to barrel of spillway. In the other word, When, flow change s and move upward till full pipe condition, Pressure will change and fluctuate a lot, while crest control point transfer to orifice monitoring condition, some vibration will occur at down section of Spillway and negative pressure zone appeared and corrosion will damage inner concrete surface of spillway. For this reason, Gathering information due to this point is very important.

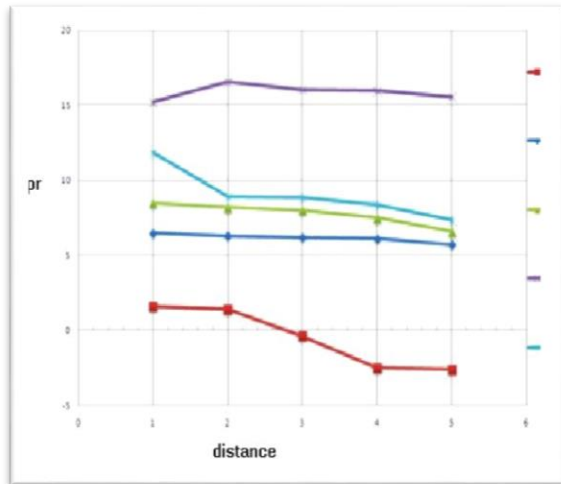
According to the study, when flow rise to near unsustainable Submersible zone, the maximum pressure negativity would be appear and the crisis situation for cavitations is this condition. For each spillway with steps chamber and different vortex breaker on the crest this situation is completely different. It means that, different spillway has different condition, but for understanding this obligation one recommend can be present, Based on this experiment, while flow will be change from crest control to orifice zone the criticality probably happens. Table (5) illustrates the dangerous zone of different spillway with various condition.

Table (5): Limitation of cavitations Risk v.s. Submersible ratio

no	Spillway type	Vortex breaker arrangement	Minimum H/re ratio for cavitations risk probability	Maximum H/re ratio for cavitations 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

According to table (5) when submersible ratio is less than 0.37 ,thencavitations Index will be more probably increased. But while steps chamber is utilized the story is going to be changed and submersible ration would be changed dramatically. Besides, shape of steps has great effect on flow variation regime. Some normal equation could not be achieved and strongly recommend that for each type of steps some experiment should be run.

Figure (14): pressure (on manometer) on crest of spillway to body of shaft



CONCLUSION

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

Maximum risk of flow rate is magnitude at $1/3$ down side of shaft, Magnitude velocity is occurred at the end steps of stepped chamber, and also will take place at $1/4$ of stepped Shaft spillway. According to simulation, height and width of each step on stepped chamber has great effect on floe regime, especially when flow regime change from nape to skimming flow

-A morning – glory spillway should be placed as far as possible from reservoir boundaries to ensure radial flow

Over the crest (Barani, G.A. and et al., 2005). 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.

Placement of piers on the crest is an efficient way of coping with the negative effects of the vortex (Micronics, Company., 2010). 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 (Novak, P. and et al. 2007).

Using Stepped Shaft spillway has effect on flow rate and in some cases, may caused flow rate increase While using stepped chamber, the cavitation risk should be considered. According to the runs, Although, stepped chamber on spillway decrease flow rate, and also stepped chamber deduce cavitations risk, using vortex breaker with ogee shape increase flow rate till 22%.

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