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The Effect of Surface Roughness on Discharge Coefficient and Cavitations of Ogee Spillways Using Physical Models

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ABSTRACT

Background: Flow spillway structure is of major issues in dam construction and type of spillway design, considering appropriate discharge coefficient and long term investigation of spillway plot hydraulic performance are highly important. **Objective:** Suitable graphs selection and supply based on type of wall roughness in different parts of peak spillways are keys to use this type of spillways in dam construction projects. To do this, using physical-hydraulic model, supreme complex of Khuzestan Water and Power Industry performed measurement tests and observed hydraulic parameters and analyzed discharge coefficient in different fields including surface roughness in Ogee spillway model. **Results:** Number of performed tests of the model with six types of surface roughness and 5 different flow rates totally include 30 tests. **Conclusion:** Finally, increase of relative roughness of spillway discharge coefficient decreases in appropriate with surface roughness. Also in results of the experiments show in different discharges, increasing the roughness decreases the cavitations index.

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INTRODUCTION

Generally, spillways are embedded for discharge of extra water or flood which is higher than reservoir capacity to be reserved. In directional dams also, spillways are used for bypass or redirecting water flow which exceeds system capacity. Most of dams are destroyed due to lack of suitable spillway capacity or inappropriate design. In fact, if dam spillways are appropriately computed and designed, the area will not face structural instability and floods. Spillways are of structures, used in measurement water pass of canals and many other applications. This is the reason that lots of efforts have been done toward increasing accuracy of flow measurement of such structures. After a few years and considering a range of reasons, spillways have surface roughness different from the main designed one, which highly affects spillway discharge coefficient. Ogee spillways are the most ordinary and inexpensive spillways with high capability of water pass. These spillways are highly used in directional dams due to their high hydraulic efficiency (Kamanbedast ,2013). When such spillways are well-designed and constructed, they effectively pass water flow and provide accurate measurement of flow and this is the reason that water hydraulic and civil engineers use them as a measurement structure (USBR,1973,1961). For heights lower that heights of spillways design, flow rate of the spillway decreases due to resistance of the head against water flow and flow rate increases in higher heights and this is a cue to cavitations because it produces lower vapor pressure (Abrishami ,2006). Also, in this case, water flow has high kinetic energy and supercritical flow rate which leads to construction of relaxation basins at the end of spillways. In the research, constructed a physical model of the morning glory spillway and conducted laboratory experiments to investigate the effect of the number and shape of anti-vortex piers on the discharge coefficient of the morning glory spillway. They concluded that the joint effects of an increase in the number of the blades will increase the discharge capacity of the morning glory spillway (Mousavi, *et al*., 2013). Determine the Appropriate Location of Aerator System on Gotvand olia dam's Spillway Using Flow 3D(physical models of the spillway, conducted laboratory experiments and concluded that the cavitations index),(Erfanian Azmoudeh, *et al*., 2012) . Discharge Coefficient and near optimal arch dam shape for the Morning Glory Spillway Using Artificial Neural Network and concluded the positive effect of anti-vortex piers on the spillway discharge coefficient has studied. In above researches, circular spillways have been used. In this study examines the effect

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of number and angle of Anti-vortex piers on submergence threshold in the square morning glory spillways and in crest control condition using physical model. Also for comparison, a series of experiments have been performed on a circular spillway. (Kamanbedast, 2012),(USBR,1990).

Ogee spillway:

A weir is defined as an obstruction in an open channel that water must flow over and is used as an indirect method for obtaining the flow rate based on the weir geometry and head on the weir crest (King and Brater,1963) Ogee spillways are of reserving dams spillways, as discussed in this paper. These spillways are of common spillways used in dams.

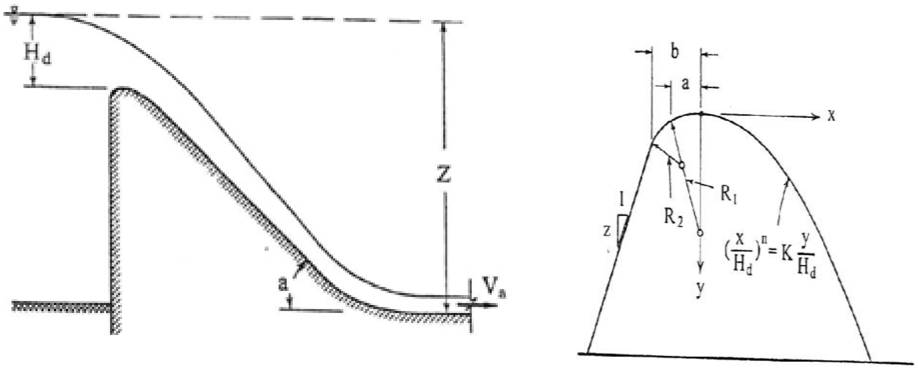

Fig. 1: Ogee spillway.

Ogee spillways are of the most important and common dam spillways. Ogee spillway has a control crest in curved form or with S profile. Typically, upper limit of the curved is designed in a way that it will be closer to lower profile of water pass which is aired on a sharp crest and in appropriate with water pass. Preventing air entering under the water pass, there is a contact between spilled water and spillway head profile. For flow rates such as design height, water passes to the boundary layer and moves slowly on spillway head profile and reached maximum discharge efficiency. Lower than upper limit of joint curve, profile continues along a slope in a parallel way and protects water sheet on water shed surface. At the end of slope, a reversed curve returns water flow to relaxation basin or spillway discharge canal. Upper curve of spillway head can be selected faster or slower than water shed profile. Slower form of profile results in a coherence of water with profile surface and production of positive hydrostatic pressure. In this state, flow resistance increases and spillway discharge efficiency decreases. For faster profile, it is possible to separate water sheet from head surface which produces negative pressure on surface. These negative pressures are notable with height increase which increases flow rate. A spillway head with downstream apron can be used as a complete spillway. This mode can be observed in concrete dams. In other mode, water shed head may be used for other spillways just as a control structure. Since, overtopping and Ogee spillways cross section obtained from water flow lower surface curve on the spillway of rectangle sharp crest, we can use its discharge to determine discharge of spillway of rectangle sharp crest. Equ. (1).also the cavitations' index can be calculated with Equ.(2). (Kamanbedast ,2013)

$$Q = CLH^{1.5} \tag{1}$$

And

$$\sigma_c = \frac{p - p_v}{\rho \frac{v^2}{2}} \tag{2}$$

$$\frac{Y}{H} = -K\left(\frac{x}{H}\right)^n \tag{3}$$

$$L = L' - 2(NK_P + K_a)H_e$$

First formula relates to flow rate equation which is highly similar to flow rate equation in morning glory spillways and the only difference is in spillway length. The second equation relates cavitations' index and of the third is to ogee profile and effective length of spillway.

Methodology:

In modeling for physical phenomenon, first we should recognize important relations and parameters concerning studied process based on information, researches and experiences. Then, dimensionless relations should be classified using dimensional analysis techniques in an appropriate form. In this research, Buckingham theory was used for dimensional analysis. These relations let us to decrease number of variables and to use results for all modes. Follow the following points for dimensional analysis of flow:

- Repetitive variables should have all dimensions of related variables
- Select repetitive variables in a way that are possible to measure them in laboratory with acceptable accuracy (including: tube diameter)
- One of repetitive variables should be of fluid features (ρ, μ, ν). And if there are no such variables, use acceleration of gravity parameter (g) as repetitive variable.
- One of repetitive variables was selected from flow feature (Q,V)
- One of repetitive variables was selected from length (flow depth, structural height or tube diameter and etc.)
- We can multiply two dimensionless parameters and find a new dimensionless parameter

Considering above key points, it conclude the following equation:

$$f_x\,(cd, Q, p, H, \rho, \nu, g, \mu, \varepsilon) = 0 \tag{4}$$

in which, dc is spillway coefficient, Q is flow rate, P is spillway height, H is water height on the spillway, p is fluid density, v is water speed on the spillway, g is acceleration of gravity, μ is viscosity of the fluid and finally, ε is spillway surface roughness.

Considering resulted relations, parameters are as follows:

$$f\,(Cd\,, \mathrm{Fr}, \mathrm{h/P}, \frac{\varepsilon}{\mathrm{P}},, \mathrm{Re}, w_e) \tag{5}$$

Which finally in this research, parameters including It Weber number and Reynolds number are ignored in order to simplify and decrease number of tests and parameters. The following dimensionless parameters were considered upon performing a series of tests on these models.

$$Cd = f\,(\mathrm{Fr}, h/\mathrm{P}, \frac{\varepsilon}{\mathrm{P}}) \tag{6}$$

In using condition, the dimensionless parameters of cavitations index ($\boldsymbol{\sigma_c}$) also calculated.

To reach considered results of this paper, Authors used hydraulic laboratory equipments of Khuzestan Water and Power Industry Higher Education and Research Complex and characteristics of such equipments are as follows:

7.5 m flume with 30 cm width and 45 cm height, made in Germany by Gunt Company, equipped to flow rate meter and pitot tube to read input flow rate of flume with details mentioned under the image. Fig. 2

Fig. 2: 7.5 m flume which is set up and implemented in laboratory.

Level gauge was used to measure depth and water surface elevation of canal flow. Level gauge was used to measure depth and water surface elevation in all spots of canal flow. Spillway profile of this device is in coordination with standard spillway profile (WES). Spillway is made of PVC which is appropriate for daily applications for research and education. To do this and also to reach research and educational goals, Ogee spillway can be set up in laboratory flume and it can be fastened to base plate. It is to be noted that this spillway can be used without base plate.

Ogee spillway with Manometric panel includes: Fig. 3

1. Spillway body
2. Manometer panel in mm scale
3. Manometer numbers, each attached to measurement cavity located behind the spillway
4. Pressure measurement cavities
5. Special knots of device

To do considered research, it is firstly described with physical model and Ogee spillway and discharge coefficient was computed with 5 different flow rates and then, it is repeated with different roughness in addition to natural state of spillway and finally, required processing is performed. After all, it draws relation of discharge coefficient with relative roughness and height of water on spillway and Froude number. Note that to reach considered roughness on spillway surface, use a range of emery with specified roughness percentages, some samples of which are in following figure. All tests performed for this paper are as follows: Table 1.

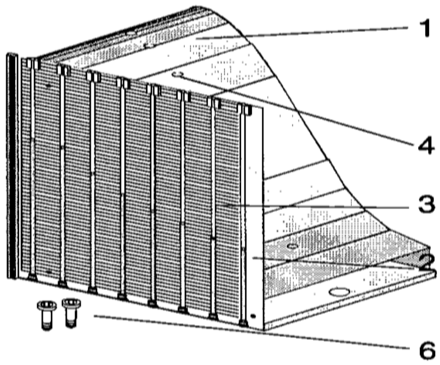

Fig. 3: Manometer plate.

Table 1: Variables and number of tests performed to compute spillway coefficient.

R	Descriptions	Number
1	Flow rate 5,10,15,20,25 m^3/h	5
2	Spillway	1
3	Roughness 1.2,1.8,2,2.5,3.6 mm	6
4	Total tests	30

At first, using control valve of input flow rate and reading flow rate meter, embedded on flume, it proved 5 cubic meters per hour flow rate and after a few minutes and stability of flow conditions, fluid depth in spillway upstream and water height on spillway were measured and sited in table. Then, increasing flow rate up to 10 cubic meters per hour and after stability of flow conditions, it did the same process and sited results. It also did the same work for flow rates in 15, 20 and 25 cubic meters per hour and sited results in table. It sited all results related to first mode in related tables.

Fig. 4: How to create roughness on spillway surface.

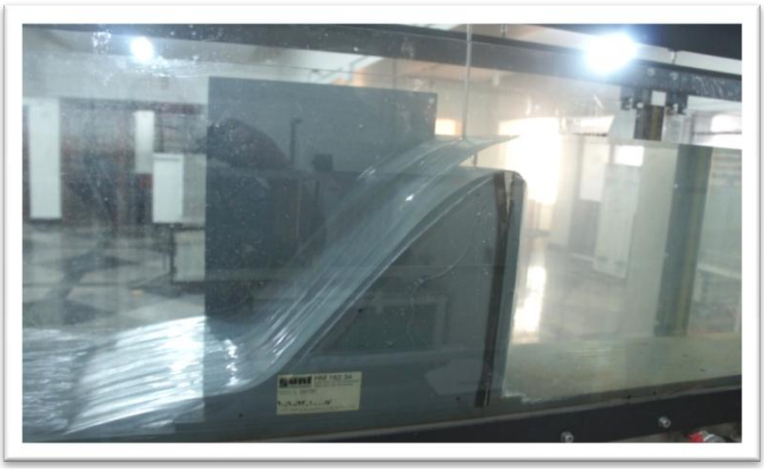

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Fig. 5: Spillway that used in the experiments.

Discussion:

The results of the analysis of experimental data are presented in Figures (diagrams) and tables. To do tests and to examine, a series of tests on a flat surface (with no roughness) were performed on spillway and the results of examination and comparison were used with a range of roughness. Based on tests, relation proof of scale flow rate and spillway coefficient is presented in the following graph: **Fig. 6**.

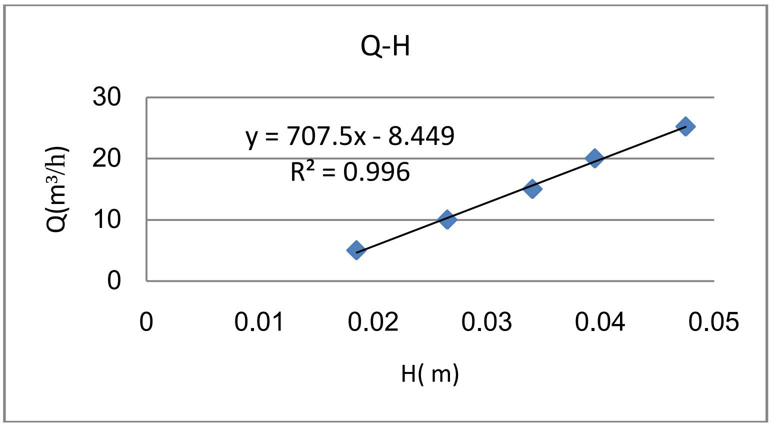

Fig. 6: Relation of scale flow rate for spillway with flat bed.

After performing tests for spillway with flat bed, it performed tests for spillway with rough bed which it used types of roughness with different heights and it used emery with different roughness and following table shows heights of these roughness. Table 2.

Table 2: Characteristics of types of roughness through tests.

R	Roughness height of the overflow (e / p) percent	Classification of roughness	Roughness height	Description
1	0.35	Very low	1.2mm	Roughness Type I
2	0.53	Low	1.8mm	Roughness Type II
3	0.58	Average	2mm	Roughness Type III
4	0.73	High	2.5mm	Roughness Type IV
5	1.05	Very high	3.6 mm	Roughness of V

Consideration of roughness effect in form of figure 7, shows results of roughness coefficient increase than spillway coefficient. As noted before, it used dimensionless parameters in designing process. Increasing roughness leads to decrease of discharge coefficient because increase of roughness in fixed flow rate leads to increase of water height on spillway and finally decreases c_d.

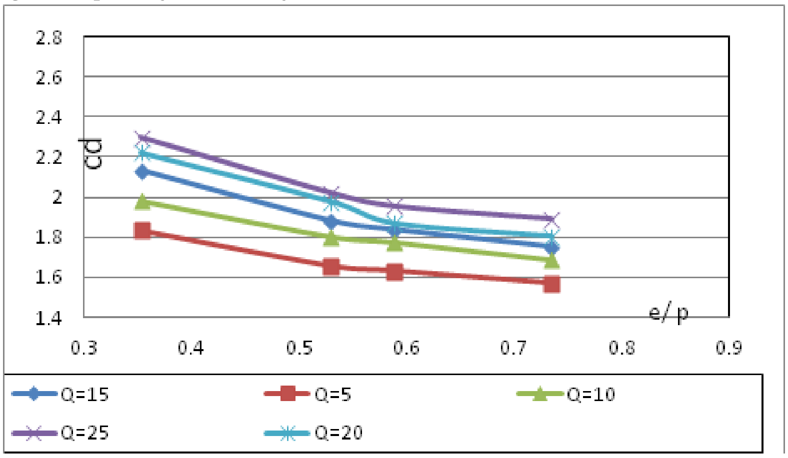

Fig. 7: Relation of effect of spillway relative roughness than discharge coefficient.

In conditions without considering roughness, research results show that the most effective factor of water pass coefficient is relation of upstream water load than spillway radius and increase of this relation, increases water pass coefficient. Also, variations of relation of head height than total load on spillway have no significant effect on discharge coefficient. Variations of discharge coefficient (C_d) in case of fixing all other conditions including spillway head elevation and its curve radius and any other hydraulic conditions with regard to the mentioned form, increase of spillway relative roughness results in decrease of discharge coefficient. Reason of such variations refers to effect of roughness on flow conditions. Because increase of spillway body and sidewalls results in tendency of flow to rough bed and finally, higher coherence of speed profile on spillway head and reduction of negative pressure area are expected. Moreover, as shown by curves, effect of relative roughness on discharge coefficient is less than flow rate.

Roughness influence on cavitations:

According to these tables,(3,4),(results of the experiments) in different discharges, increasing the roughness decreases the cavitations index . Remember that critical index was 0.2.tables 3,4.

Table 3: The result of pressure on flow parameters and σ_c.

Experiment report												
Roughness(smooth)								Cavitations index	Critical velocity m/s	Head on spillway	discharge m³/h	num
P_8	P_7	P_6	P_5	P_4	P_3	P_2	P_1					
								σ_c		cm		
5	11.5	7.5	25.5	27.5	29.5	29.5	30	34.44	2.31	1.85	5	1
5.5	11.5	8	25.6	28	29.5	30.5	31.1	8.61	4.63	2.65	10	2
7.2	12	20.5	25.5	28	29.5	30.5	31.7	3.88	6.94	3.4	15	3
8.8	12	20	25.9	28	29	30.5	32.4	2.18	9.26	3.95	20	4
8.4	10.5	12	18.5	26.5	27	29.5	31	1.38	11.57	4.75	25	5

Table 4: The result of pressure on flow parameters and σ_c(roughness surface).

Experiment report												
Roughness(3.6mm)								Cavitations index	Critical velocity m/s	Head on spillway	discharge m³/h	num
P_8	P_7	P_6	P_5	P_4	P_3	P_2	P_1					
								σ_c		cm		
5.5	11.5	3	25.5	27.5	15	20	22.5	34.21	2.31	2.5	5	1
4	15.8	4	25.5	28.5	17	20.5	21.5	8.58	4.63	3.5	10	2
-	5.5	10	5.5	26	28	14.5	15.5	3.84	6.94	4.5	15	3
-	10.5	11.5	25.5	28	13	20	25.5	2.16	9.26	5.1	20	4
12.5	12.5	9	26.5	28	11	21	23	0.61	11.57	6.4	25	5

Conclusions:

Conclusions which can be drawn from this research through investigating and analyzing the above tables and figures are as follows: In this research, after identification of significant and effective parameters affecting discharge coefficient of Ogee spillway using dimensional analysis methods obtained from dimensionless equations and finally performing about 30 tests on Ogee spillway with certain geometrical features and a range of operated roughness, it reached the following results:

1. In terms with no roughness, research results show that most effective factor for discharge coefficient refers to upstream water load than spillway radius and increase of this relation results in increase of discharge coefficient.
2. Increase of relative roughness of spillway results in decrease of discharge coefficient of flow and effect of relative roughness on discharge coefficient is less than flow rate.
3. By examining the relationship σ_c and roughness ,the tables show that in all cases σ_c increasing the surface roughness is decreased.

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