An Experimental Study for Radial-Gated Ogee Spillway Discharge and Comparison with Other Model Studies

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Abstract: - The book *"Design of Small Dams"* is a renowned reference publication used for the design of dams in America and it is commonly used in Turkey as well. Flood spillways of many dams are ogee profile radial-gated weirs, and accurate calculation of discharges passing over a partially open radial-gated ogee spillway is important in flood routing computations. Because each spillway and its appurtenant structures have geometrical and hydraulic properties peculiar to their own, a generalizable method for calculating the discharge over a partially open radial-gated spillway should not be realistic. Therefore, many laboratory experimental studies are done both in America and in Turkey for more accurate calculation of spillway discharge of dams individually. With the objective of comparing the results of these studies and the method given in that book another experimental study is performed as summarized in this paper. For this purpose, experiments for the partially open radial gate in a laboratory setup having a 95 mm high, 10 cm wide ogee spillway model with an adjustable radial gate of proportionate dimensions both placed in a 5 meter long, 10 cm wide and 30 cm high channel are done with many combinations of flow rates and gate openings as allowed by the physical dimensions of the open channel setup available in our laboratory and the maximum flow rate its pump can generate. Taking a scale ratio of 1/100, the relative differences of the discharge coefficients given in the above-mentioned book from the experimental discharge coefficients measured in this study for the same configurations are found to be between +3% and +34%. Although the discharge coefficients determined by this experimental study are not too deviant from those obtained from 15 laboratory model studies done by the United States Bureau of Reclamation and the United States Army Corps of Engineers in America and seven such studies done by the State Water Works in Turkey, it is concluded that the discharge – head relationship of a radial-gated spillway of a dam should be determined by a laboratory experiment on a model of not too small a scale, and a generalized method cannot be applicable to all spillways in the world as a whole.

Key-Words: - Radial-gated ogee spillways, discharge over partially open radial-gated ogee spillways, discharge coefficients of radial-gated ogee spillways, crest profiles of ogee spillways, radial-gated ogee spillway model, Froude similarity between model and prototype, open channel flows.

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1 Introduction

Flood spillways of almost all dams in Turkey have ogee profiles described in [1], [2] and a majority of them are equipped with radial gates [3], [4], [5]. Because it is an orifice flow under a gate of circular arc rather than a planar sluice, flow under a partially open radial gate over an ogee spillway is more complicated than the fully open (free flow) case. In spite of this fact, the former needs only one chart for the discharge coefficient, while the latter has three charts, [1]. An explanation of the method for the fully open case with numerical examples is given on seven pages, while the explanation for the partially open case is given on one page only, where there is a figure depicting the discharge coefficient. This figure in [1] is a replica of the same figure in [6]. In this figure, there are widespread noises of the plotted points around the fitted curve for the case where the gate seat is a little downstream from the spillway apex, which was drawn using the data measured only on two laboratory model spillways and three spillways of actual dams, [6]. The curve for the case where the gate seat is at the apex is drawn based on only one laboratory model data [6].

The equation given both in [1] and in [6] for the discharge passing through a partially open radial gate over an ogee spillway, which is a dimensionally homogeneous equation, is:

$$Q = C \cdot D \cdot L \cdot (2g \cdot H)^{1/2} \quad (1)$$

where, C is the discharge coefficient, D is the shortest distance between the gate lip and the spillway crest curve, L is the net length of the spillway crest, and H is the vertical difference between the total head just upstream of the gate (including the velocity head of approach) and the center of the gate opening. The relevant figure in [1] gives C as a function of the angle (ϴ) between the tangent to the gate lip and the tangent to the crest curve at the point closest to the gate lip. Computation of this angle ϴ and of D is fairly complicated and requires involved trigonometric and geometric analyses. A long numerical and analytical algorithm is suggested in [6] for computations of both ϴ and D, which requires (1) manually plotting both the crest coordinates and the slope function of the analytical ogee profile in a log-log scale millimetric graph paper and visually reading the numerical values out of this chart, (2) replacing the analytical expression of the downstream part of the ogee profile by arcs of three circles of different center points and radius lengths, (3) doing computations on a numerical table comprising 20 columns for the gate opening D and of the angle ϴ, and (4) doing computations on another table having 15 columns for ultimately determining the discharge Q, [6]. This manual method, which is advocated by [1] also, presents an archaic approach as if we were in 1950s and 1960s and it will definitely take a long time and a large effort improper to the current age of computers. Another deficiency of this method is that it does not present any algorithm for a possible case where the closest point between a partially open gate lip and the spillway crest lies on the part of the crest curve upstream from the spillway apex which is part of a circle and not the curve depicted by the analytical expression defining the downstream face of an ogee spillway. A real-life example to such a case is the radial gate of Yellowtail after Bay Dam in Montana USA when the gate opening is 6 ft, [7].

There should exist many ogee spillways equipped with radial gates in the world, and controlled releases of floods of moderate magnitudes through partially open radial gates should be a common practice. Hence, accurate computation of discharges under partially open radial gates is an important problem. There are two issues about the computation of discharge passing under a partially open radial gate over an ogee spillway. First, the curve proposed in [1] is not sufficient for a general application because it is developed using the measurements on three actual-size spillways and two laboratory models only. Besides, even in its present form, the observed points have large noises around the fitted curve, especially for values of angle ϴ smaller than 73º, [6]. Secondly, the method advocated in [1] for computing the flow rate is too cumbersome, intricate, and time-consuming as explained in the previous paragraph. To remediate the old-fashioned and winding method of computation for Q in equation 1, a novel analytical and numerical algorithm was proposed in [7], and unfortunately, it has gone unnoticed so far although it presented a modern method which is executed in a split second in an ordinary computer requiring neither initially prepared manually-drawn graphs nor numerical tables with many columns, [7].

To probe into the apparent problem of doubt for the relevant figure in [1] about its being a general chart applicable to any spillway in the world, a study was performed whose details and results are in [8]. In that study, using data from 6 reports of laboratory model studies done by the United States Bureau of Reclamation, 9 such reports done by the United States Army Corps of Engineers, 6 such reports, and one report of measurements directly on the flood spillway of Seyhan Dam done by the Technical Research and Quality Control Department of the State Water Works of Turkey, all having radial-gated ogee spillways, the experimentally determined discharge coefficients for partially open gates were compared with those given by the method of [1], whose results revealed large differences between the two and there did not seem to have a generalizable chart. In that study it is concluded that a general chart is not possible, and the best thing to do is to obtain the chart for the discharge coefficient peculiar to each spillway by doing laboratory measurements of all relevant quantities on not too small a model [8]. It is further recommended that measurements in the approach channel of actual spillways during days of incoming floods should be taken because recent technology would allow such measurements at reasonable costs with no danger to life, [8].

Recently, we have had an open channel setup built by a professional laboratory equipment manufacturing company with dimensions of 5 m length, 10 cm width, and 30 cm wall height. The channel is rectangular and it has a self-circulating water flow provided by a bottom storage tank and a pump of suitable capacities. On the pipe supplying the flow to the upstream entrance of the channel, there is a high-precision flow meter for measuring the circulating discharge. Figure 1 shows the photograph of this open channel model. Recently, we did experiments for a partially open radial gate in this laboratory setup on an ogee-profile spillway model having a height of 95 mm and a width of 10 cm and an adjustable radial gate of proportionate dimensions mounted to the top of the side walls above the spillway with the help of screws placed in the middle of the channel with many combinations of flow rates and gate openings, [9]. The maximum model flow rate was chosen so that the upstream water depth would not exceed the wall height of the channel, and the minimum discharge was determined so that the spillway flow would not be free flow with a gate opening of 1 cm. By trials, we have determined the maximum radial gate opening as 4.5 cm so that with that opening and the maximum flow rate the upstream water depth would not overflow the channel wall. We decided that increments of 0.5 cm for radial gate openings were sufficient for our experiments. We had two objectives in our study: (1) to observe how close the discharge coefficients to be measured on this laboratory model would be to the ones observed in those 22 detailed laboratory studies done by prestigious organizations in America and in Turkey, and (2) to check the agreement of the generalized method for the discharge coefficient for the case of partially open radial-gated ogee spillways given in [1] with the ones observed experimentally on those laboratory studies.

2 Material and Method

2.1 Data of 21 Models and One Actual Spillway of Previous Studies and of the Model of this Study

All relevant geometrical and hydraulic data of 21 laboratory model spillways and one actual spillway presented in the technical reports cited in [8] are the initial part of the material used in this study. We obtained permissions from these three organizations for the usage of the data in those reports. The second material is the data obtained from the experiments done with 29 combinations of flow rates and gate openings in the laboratory setup of this study. The ranges of flow rates and gate openings were constrained by two criteria: (1) the upstream flow depth would not exceed the wall height of the channel and (2) the gate opening would be lower than the free flow formation. The flow rates generated in the setup were 150, 130, 110, 90, 70, 50 liters/minute, and the vertical gate openings were between 1.0 cm and 4.5 cm at 0.5 cm increments, [9]. Measurements of the relevant quantities were done in a few minutes after each setting when the flow conditions and the overall water surface profile became steady. Figure 2 shows the instant of one of the experiments. As seen in Figure 2, the radial gate is free to move up and down with the help of a steel rod. The vertical distance between the lower tip of the gate and the apex of the spillway and the flow depths were measured by a millimetric depth measurement gauge, [9].

The minimum flow rate and the minimum gate opening generated in the experiments were 0.0008333 m^3/s (= 50 lt/min) and 0.01 m. Because the kinematic viscosity of water is: $\nu \approx 1\times10^{-6}$ m^2/s, the Reynold Number of the flow passing over the 10 cm wide spillway under a 1 cm opening is: Re = 8333. The Re magnitudes for all other flows in the channel and under the gate are greater than 8333 and about 25,000. Therefore, all the flows in all conditions of our experiments were turbulent (Re > 2000).

Because the widths of both the spillway and the inner side of the rectangular channel were 0.1 m, we assumed the scale of the model to be 1/100. Hence, ours was a single gate, single opening spillway corresponding to a prototype dimension of 10 m. Applying the Froude similarity principle to this setup with a length ratio of $L\text{p}/L\text{m}$ = 100, the relationship between the prototype and the model flow rates becomes:

$$Q\text{p} = Q\text{m} \cdot (L\text{p}/L\text{m})^{2.5} = Q\text{m} \cdot 10^5 \quad (2)$$

Here, the subscripts p and m denote “prototype” and “model”. The maximum flow rate we could obtain in this setup without flowing over the side walls was 150 liters/minute, and this corresponds to a prototype flow rate of 250 m^3/s. The steady conditions for a combination of flow rate and gate opening were reached in a few minutes, and the circulating discharge was read from the built-in flow meter in liters/minute. Altogether 29 combinations of flow rates and gate openings were configured during the experiments.

Fig. 1: Photograph of the open channel model setup used in the experiments

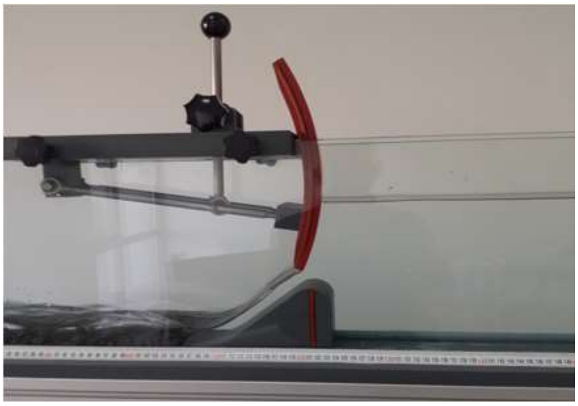

Fig. 2: Instant of one of the experiments of flow passing under the partially open radial gate.

2.2 *n* and *K* Coefficients of the Downstream Crest Curve of the Model Spillway

The analytical expression of the crest curve of the downstream face of an ogee spillway is [1]:

$$y = K \cdot x^{\mathrm{n}} / Hd^{(\mathrm{n}-1)} \tag{3}$$

where, y and x are the ordinate and the abscissa of any point on the downstream profile with respect to a coordinate system whose origin is at the apex and the ordinate axis is downwards in m, *Hd* is the total head with respect to the spillway apex for the design discharge in m, and *n* and *K* are the coefficients. We placed the model spillway on a large millimetric graph paper, drew its profile on the paper, and carefully read the abscissa and the ordinate coordinates of both of its downstream and upstream faces. We computed the *n* and *K* coefficients for our model spillway by the Least-Squares method so as to match its downstream profile to the curve defined by equation 3 as close as possible. The sum of squared differences between the measured ordinates of N number of points on the downstream face and those defined by equation 3 is:

$$\mathrm{SSR} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \left\{ \mathrm{y\ theoretical}_i - \mathrm{y\ measured}_i \right\}^2 \tag{4}$$

Denoting y $\text{measured}_{\mathrm{i}}$ by y_{i}, for the ogee profile, SSR becomes:

$$\mathrm{SSR} = \sum_{\mathrm{i}=1}^{\mathrm{N}} \{K \cdot \mathrm{x}_i{}^{n} / Hd^{(n-1)} - y_i\}^2 \tag{5}$$

The best fit *n* and *K* coefficients are those minimizing SSR, and for that both partial derivatives of SSR with respect to *n* and *K* must be equal to zero. Taking ∂SSR/∂*n* and ∂SSR/∂*K* analytically and equating them to zero, a system of two nonlinear equations result, which in algebraically concise forms are as given below.

$$\sum_{\mathrm{i}=1}^{\mathrm{N}} \{K \cdot \mathrm{x}_i{}^{2n} / Hd^{(n-1)} - x_i{}^{n} \cdot y_i\} = 0 \tag{6a}$$

$$\sum_{\mathrm{i}=1}^{\mathrm{N}} \{K \cdot \mathrm{x}_i{}^{n} - y_i \cdot Hd^{(n-1)}\} \cdot \{\mathrm{x}_i{}^{\mathrm{n}} \cdot [\ln(\mathrm{x}_i) - \ln(Hd)]\} = 0 \tag{6b}$$

Solution of this system by the iterative Newton-Raphson algorithm beginning with initial estimates taken from [1] always gives convergent cycles with a precision of six significant digits in both roots. The magnitudes of *n* and *K* coefficients of the ogee spillway having a height of 9.5 m and a width of 10 m for a design discharge of 250 m^3/s and Hd = 5.642 m turn out to be: n = 1.618 and K = 0.8289. Figure 3 shows the actual downstream profile and the one depicted by equation 3 with these coefficients.

2.3 Experimental and Theoretical Discharge Coefficients

The discharge coefficient which occurred for a combination of flow rate and gate opening in our experiments, *C*experimental, was computed by the equation below, which is the arranged form of equation 1.

$$C\mathrm{experimental} = Q / [D \cdot L \cdot (2g \cdot H)^{1/2}] \tag{7}$$

We computed the angle between the tangent to the gate at the gate lip and the tangent to the crest curve at the point closest to the lip (Θ), the shortest gate opening between the gate lip and the spillway crest (*D*), and the theoretical discharge coefficient (*C*theoretical) for any one of 29 combinations using the method devised in [7].

3 Results

Table 1 (Appendix) presents the numerical results of the experiments summarized above.

In [8] the experimentally determined discharge coefficients are presented against the angle Θ for all combinations of flow rates and gate openings covered in the reports of those 21 laboratory models plus one full-scale spillway mentioned in subsection 2.1 above. Together with all the coefficients in all of those 22 reports of the previous studies, we plotted the 29 discharge coefficients which we experimentally determined in our laboratory setup against the angle Θ all in the same figure, which is Figure 4. This figure succinctly presents the results of so many laboratory studies done by prestigious organizations in America and in Turkey together with the results of our study. Our conclusions and discussions are given based on these results in the ensuing sections.

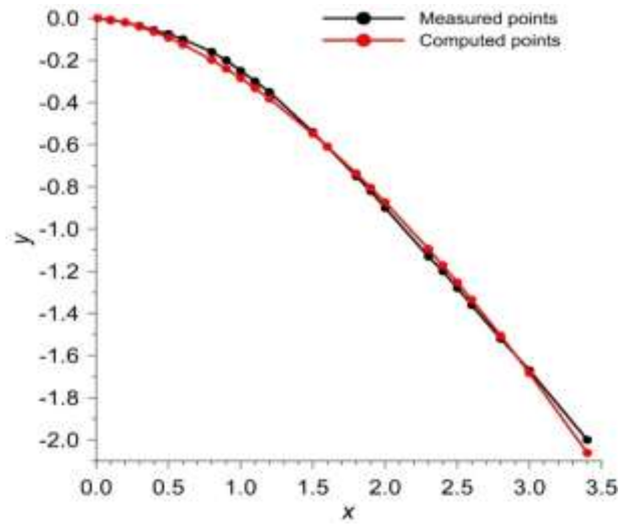

Fig. 3: The measured points and the points computed by the analytical expression for the downstream face of the model ogee spillway whose n and K coefficients are determined by the Least-Squares method

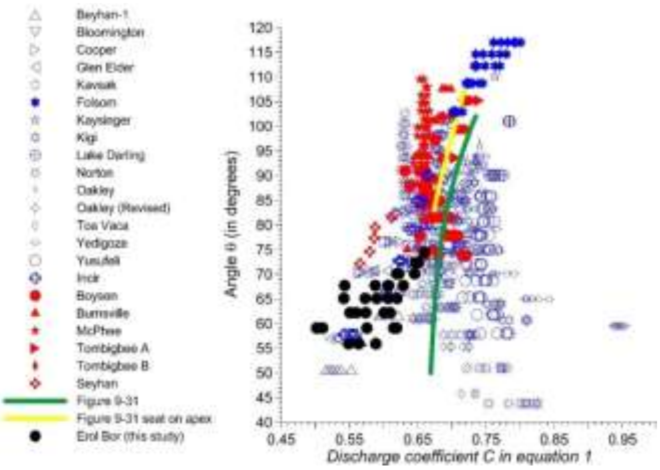

Fig. 4: Plots of the discharge coefficients against the angle ϴ obtained by the measured data analyzed in [8], of the discharge coefficients obtained in [9] and the theoretical charts given in [1]

4 Conclusions

There are two conclusions reached out of this study which are presented below.

(1) The curves given in [1] cannot be generally applicable. First, the curve for the case where the spillway bottom lip is on top of the spillway apex was obtained from one (only one) laboratory model, not even a single actual-sized spillway. Second, the curve for the case where the spillway seat is a little further downstream from the spillway apex is the best-fit curve to the measurements on three actual spillways plus two model spillways. Besides, there are considerably wide noises of the plotted points about this best-fit curve for ϴ angles smaller than 73º, which is clearly visible in the relevant chart given in [6]. As seen in Figure 4 here, the plotted points of the experimentally determined discharge coefficients obtained by prestigious organizations in America and in Turkey from laboratory model studies exhibit very wide dispersions around a prospective generalizable curve.

(2) When the plotted points in Figure 4 are examined closely, it is noticed that both with our experimental results and with those of the previous 22 studies, there are a few different discharge coefficient (C) values against the same value of the angle ϴ. This clearly indicates that C depends not only on ϴ alone, but on another variable along with ϴ. For example, with our experiments, there are three different C's against ϴ=56º, four different C's against ϴ=59º, five different C's against ϴ=63º, five different C's against ϴ=65º, and four different C's against ϴ=68º. In a previous study, this extra explanatory variable was found to be the ratio of the vertical gate opening to the total head with respect to the spillway apex, [8].

5 Discussions

As summarized heretofore, the discharge coefficients measured in our channel model turned out to be in the same ball park as those determined on 21 laboratory models by prestigious organizations in America and in Turkey and one actual spillway in Turkey. This finding supports our final comment that the discharge coefficients for various combinations of flow rates and gate openings must be determined individually based on laboratory model studies with not too small (model)/(prototype) length ratios because the ogee spillway of each dam has unique peculiarities affecting the (head)↔(gate opening)↔(flowrate) relationship like differences in geometrical shape, length, and roughness of the approach channel, geometrical shapes of the approach abutments, geometrical shapes and numbers of the piers, angle of inclination of the upstream face of the spillway, and position of the spillway with respect to the embankment.

In light of all the previous experimental studies summarized heretofore and of our experimental study, it is obvious that the method described in [1] for computing the discharge flowing over a partially open radial-gated ogee spillway is not sufficient for accurate calculation of the flow rate, and it needs to be amended by relating the discharge coefficient to both the angle ϴ and to the ratio of the gate opening to the total head with respect to the spillway apex.

This relationship should be obtained individually for each dam.

As seen in Figure 4, the experimentally obtained values of the discharge coefficient (*C*) extend farther away from the generalized curve (green line in Figure 4) given in [1] both upwards and downwards as well as sideways. This is another indication of the lack of the method of [1] being generally applicable.

There are as many as 40 relevant publications cited and referenced in [8]. They are not repeated here to save from the length of this paper.

A study of similar theme can be mentioned as another case emphasizing the significance of such experimental studies in determining the appropriate discharge coefficients of spillway-type hydraulic structures, [10].

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APPENDIX

Table 1. Discharge coefficients of equation 1 experimentally measured in this study, those theoretical ones given by [1] for the same configurations, and the relative differences of the latter from the former (Relevant dimensions of the corresponding prototype are presented first)

Net spillway length: 10 m, sill height of spillway: 9.5 m,
angle with vertical of the upstream face of spillway: 0º,
bottom elevation of the approach channel at the upstream face of the spillway: 100.0 m,
spillway apex elevation: 109.5 m,
spillway design head: 5.642 m,
abutment contraction coefficient: 0.0,
piers contraction coefficient: 0.0,
radius of the radial gate: 31.4 m,
radius of the circle of the spillway crest profile upstream of the apex: 2.0 m,
magnitude of *n* coefficient of the downstream crest curve: 1.618,
magnitude of *K* coefficient of the downstream crest curve: 0.8289,
elevation of the center of the gate trunnion: 114.5 m,
elevation of the gate seat: 108.5 m,
elevation of the top of the gate at closed position: 139.5 m.

Gate Opening (m)	Flow rate (Q) (m^3/s)	Upstream flow depth w.r.t. spillway apex (m)	*C*experimental (this study)	*C*theoretical*	Relative difference (%)
1.0	150	14.86	0.5887	0.6712	+14
1.0	117	10.56	0.5486	0.6712	+22
1.0	83	5.46	0.5633	0.6712	+19
1.5	217	17.28	0.6190	0.6725	+9
1.5	183	12.78	0.6149	0.6725	+9
1.5	150	9.98	0.5754	0.6725	+17
1.5	117	7.88	0.5104	0.6725	+32
1.5	83	4.58	0.5018	0.6725	+34
2.0	250	16.11	0.6095	0.6739	+11
2.0	217	12.71	0.6007	0.6739	+12
2.0	183	10.21	0.5738	0.6739	+17
2.0	150	7.51	0.5598	0.6739	+20
2.0	117	5.11	0.5506	0.6739	+22
2.5	250	12.06	0.6067	0.6753	+11
2.5	217	9.86	0.5897	0.6753	+15
2.5	183	6.86	0.6197	0.6753	+9
2.5	150	5.66	0.5730	0.6753	+18
2.5	117	4.26	0.5417	0.6753	+25
3.0	250	9.53	0.6062	0.6770	+12
3.0	217	7.93	0.5877	0.6770	+15
3.0	183	5.83	0.6076	0.6770	+11
3.0	150	4.23	0.6290	0.6770	+8
3.0	117	3.73	0.5428	0.6770	+25
3.5	250	7.60	0.6222	0.6787	+9
3.5	217	6.20	0.6191	0.6787	+10
3.5	183	4.70	0.6453	0.6787	+5
4.0	250	6.28	0.6464	0.6803	+5
4.0	217	5.18	0.6510	0.6803	+5
4.5	250	5.57	0.6600	0.6820	+3

**: C coefficients given by the relevant figure in [1] for the experimental configuration*

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

Tefaruk Haktanir developed the theoretical and experimental formulation of the study. Erol Bor performed the experiments, did the computations, and presented the results in suitable forms.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

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Conflict of Interest

The authors have no conflicts of interest to declare.