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Discharge Coefficients for Radial-Gated Ogee Spillways by Laboratory Data and by *Design of Small Dams*

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ABSTRACT

Using the measured data on 15 laboratory models in USA, six models and one prototype in Turkey, the discharge coefficients (C's) of radial-gated ogee spillways for various gate openings and lake water surface elevations are computed. Comparison of these C's for 22 spillways with the ones given by Figure 9-31 of *Design of Small Dams* does not show close agreements. It is determined that C depends on both the angle ϴ and the ratio d/H_1, rather than ϴ only where d and H_1 are the gate opening and the upstream head, and statistically significant regression equations are computed individually for each one of 22 cases.

Keywords: Discharge coefficient for partially-opened radial-gated spillways.

1. INTRODUCTION

Design of Small Dams [1, 2] is a classical reference book for design of dams all over the world including Turkey [e.g. 3, 4, 5, 6]. Some dams have free-flow (un-gated) ogee flood spillways while some others have ogee spillways equipped with radial gates. The apex of a radial-gated ogee spillway is lower than the maximum operation elevation (top of the active storage), and the upper tip of the gates at closed position is usually about 1 m or so above top of the active storage. During routing of a flood the recommended operation policy is to lift all of the gates simultaneously and to have the same gate opening for all. At first glance, the total cost of a radial-gated spillway may seem to be more than that of an un-gated spillway because of the additional cost of the radial gates, their trunnion pins and hoisting mechanisms. However, a much longer free-flow spillway is needed to attain the same maximum water surface elevation (WSE) during routing of the design flood. This is because the crest elevation of the free-flow spillway necessarily equals the top of the active storage allowing a small net head for the spilling discharge. And, the excavation work needed to place the longer free-flow spillway will increase its cost. In short, comparing the relevant costs of both

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types of spillways may lead to a radial-gated one as the optimum design. There are many dams equipped with radial-gated spillways, and the routing of the critical design flood hydrograph or any other less intense hydrograph from a dam having a radial-gated ogee spillway is important both for design and for real life operations.

The methods for computing the spilled discharge over the partially-opened radial-gated ogee spillways are different in both the previous and recent editions of *Design of Small Dams* [1, 2]. The subsection 201 of the second edition of *Design of Small Dams* [1] gives the equation (a dimensionally homogeneous one) to compute this discharge as:

$$Q = (2/3)\cdot(\sqrt{2g})\cdot C\cdot L_e\cdot(H_1^{3/2} - H_2^{3/2}) \tag{1}$$

where, g is the acceleration of gravity, C is the discharge coefficient, L_e is the effective spillway length, H_1 and H_2 are defined as: "*H_1 and H_2 are the total heads (including the velocity head of approach) to the bottom and top of the orifice, respectively*." [1], and Q is the discharge. Figure 257 of the 1973 edition of *Design of Small Dams*, whose copy is given here as Figure 1, depicts the terms in equation (1) and presents a curve for the C coefficient as a function of the ratio d/H_1, where d is the vertical gate opening ($d = H_1 - H_2$). The effective length L_e is shorter than the net length due to the contraction effects on the discharging water during entrance into the spillway bays caused by the piers and the approach embankments, and it is computed by [1]:

$$L_e = L - 2\cdot(N_p\cdot k_p + k_a)\cdot H \tag{2}$$

where, L is the net length of the spillway crest excluding the piers, N_p is the number of piers on the crest, k_p is the pier contraction coefficient, k_a is the approach abutments contraction coefficient, and H is the total head above the spillway apex. Three values for k_p and k_a are suggested as 0, 0.01, 0.02, and 0, 0.1, 0.2, respectively, depending on the geometrical shapes of pier noses and abutment headwalls [1].

In subsection 9.16 of the third edition of *Design of Small Dams* [2] however, a different equation is given for discharge over a radial-gated ogee spillway while the gates are partially opened, which is:

$$Q = C\cdot D\cdot L\cdot(2g\cdot H)^{1/2} \tag{3}$$

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 (not the effective length) of the spillway crest, and H is the vertical difference between the total head just upstream of the gate and the center of the gate opening. C in equation (3) is different from the C in equation (1), and in this study we symbolize C in equation (1) by *C-73* and C in equation (3) by *C-87*. Equation (3) also is dimensionally homogeneous. Figure 9-31 on page 379 of the third edition of *Design of Small Dams* [2], whose copy is given here as Figure 2, depicts the terms in equation (3) and presents a curve defining *C-87* as a function of the angle Θ, which is the angle between the tangent to the gate lip and the tangent to the crest curve at the point nearest to the lip.

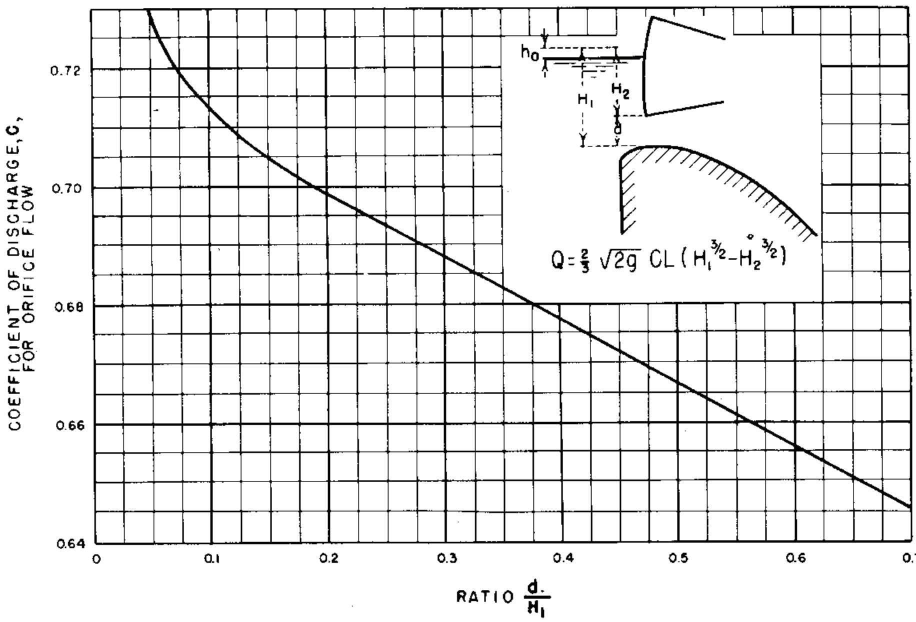

Figure 1 - Copy of Figure 257 of the second edition of 'Design of Small Dams' [1] depicting the terms in equation (1) and giving the curve for discharge coefficient C-73 as a function of the ratio d/H_1.

Equation (3) and Figure 9-31 of *Design of Small Dams* [2] are originally due to *Hydraulic Design Criteria, Volume 2, Tainter Gates on Spillway Crests, Sheets 311-1 to 311-5* by US Army Corps of Engineers [7]. Figure 9-31 of *Design of Small Dams* [2] is a replica of 'Hydraulic Design Chart 311-1' in reference no.7, whose copy is given here as Figure 3. The symbols of β, Go, and B are used in 'Hydraulic Design Chart 311-1' [7] for the symbols of Θ, *D*, and *L* in Figure 9-31 of *Design of Small Dams* [2], respectively. Otherwise, the diagrams and the numbers on both axes of these two figures are exactly the same. There are two curves in these figures, and the longer one is for those spillways where the gate seat is a little downstream from the apex, and the shorter curve is for those spillways where the gate lip is seated on the apex. 'Hydraulic Design Chart 311-1' (Figure 3 here) presents the plotted points about the best-fit curves also, which were obtained from the data taken on six cases [7].

As seen in Figure 3, the longer curve is derived using the measured data on spillways of two laboratory models and of three actual dams. It is clearly visible that the plotted points for those five cases around the best-fit curve exhibits considerable noises for Θ's smaller than 72°. The second curve in 'Hydraulic Design Chart 311-1' is derived as the best-fit curve to the points measured in only one laboratory model study, meaning a general curve is suggested which is derived out of one laboratory model only, even not an actual size prototype [7]. We believe, the relationship for such a crucial coefficient as *C-87* for the case of the gate lip being seated some distance downstream from the apex having been derived using only five cases of measured data may not reflect a true generalization, and inclusion of many more measured data may improve that relationship. Similarly, for the case of the gate seat being on the apex, data from one laboratory model is definitely too few, and the second curve in Figure 3 cannot represent the general case. This has been the main theme of our study, and accordingly we have aimed to enrichen these two relationships using many more relevant data obtained on many laboratory models performed by renowned facilities in USA and in Turkey.

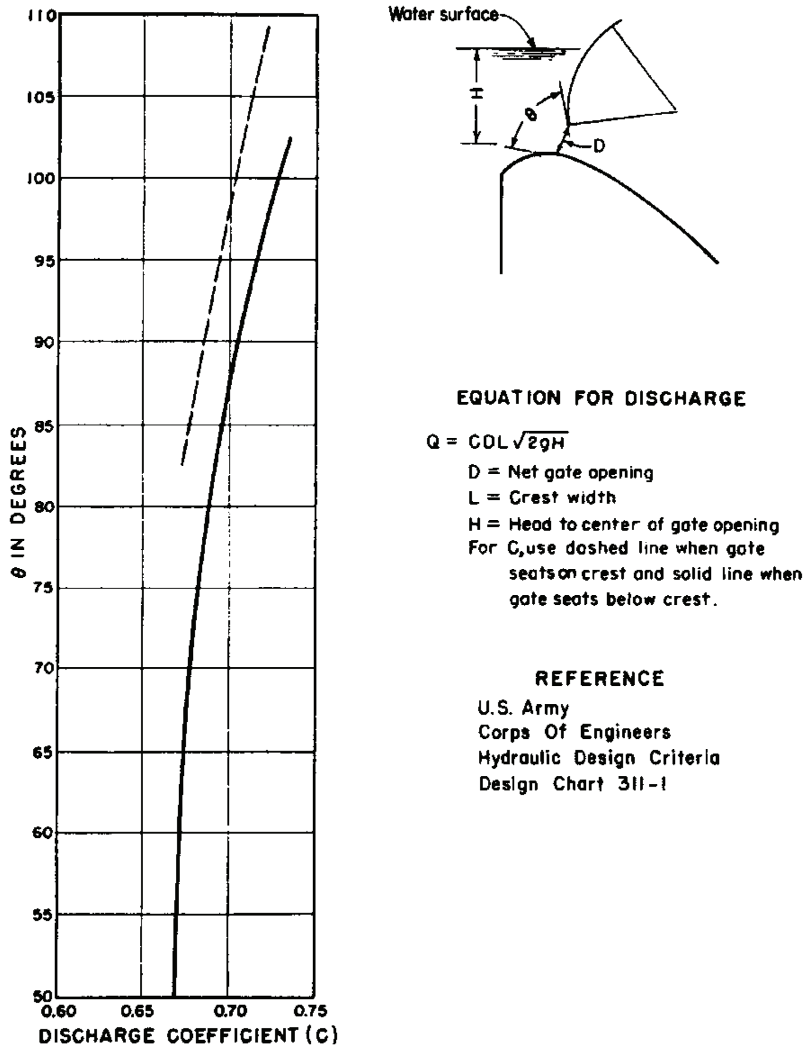

Figure 9-31.—Discharge coefficient for flow under gates. 103–D–1875.

Figure 2 - Copy of Figure 9-31 of the third edition of 'Design of Small Dams' [3] depicting the terms in equation (3) and giving the curve for discharge coefficient C-87 as a function of the angle Θ.

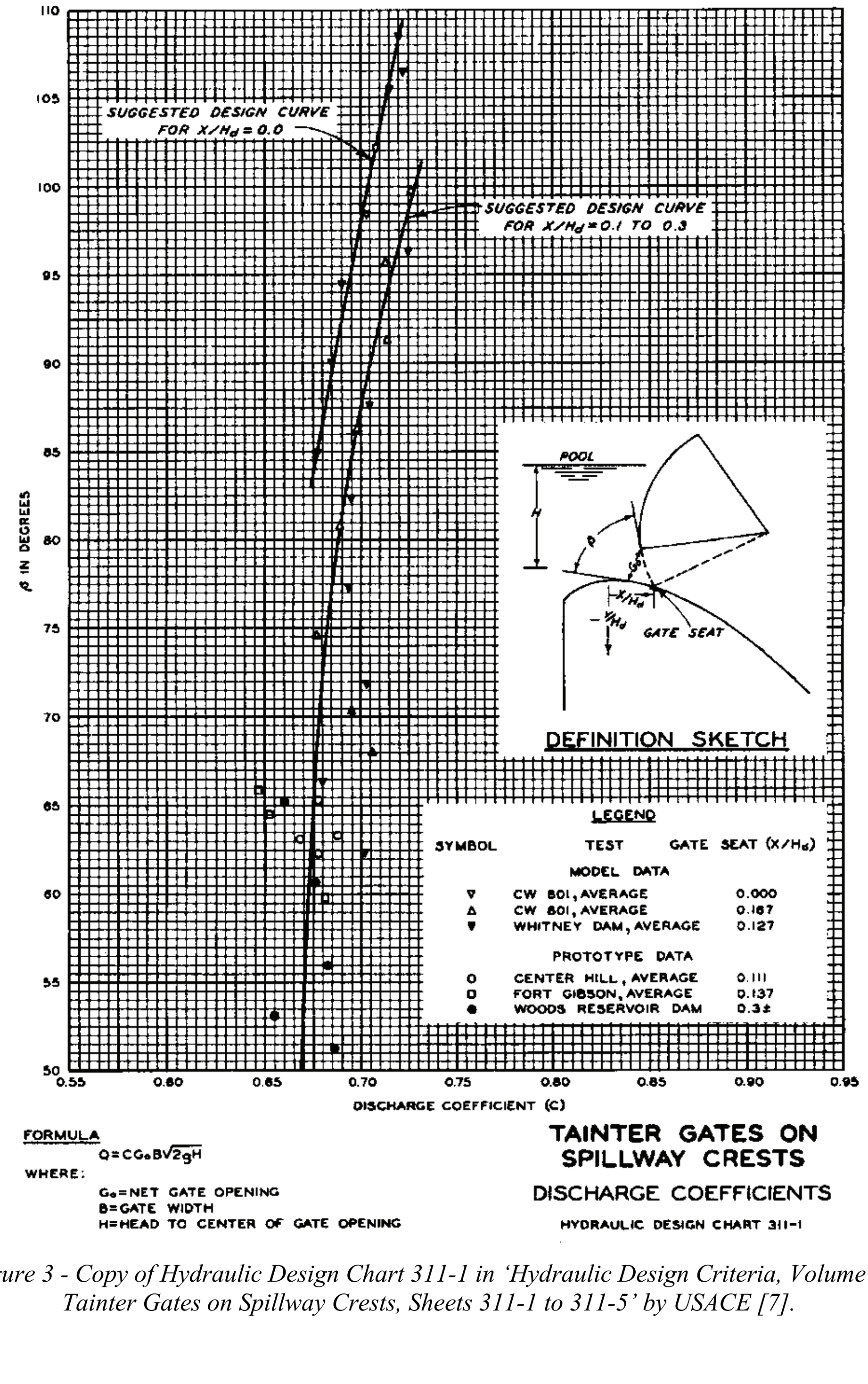

Figure 3 - Copy of Hydraulic Design Chart 311-1 in 'Hydraulic Design Criteria, Volume 2, Tainter Gates on Spillway Crests, Sheets 311-1 to 311-5' by USACE [7].

We have noticed that in designs of even the recently built dams in Turkey, equation (1) in 1973 edition of *Design of Small Dams* is used instead of equation (3) in 1987 edition of *Design of Small Dams*, although the newer edition is used for the designs of the other units of the dams [e.g. 3, 4, 5, 6]. Hence, the first objective of this study has been a quantitative comparison of equations (1) and (3) using the measured data on a few laboratory model study reports by Hydraulic Investigation and Laboratories Services of USBR, Waterways Experimentation Station of USACE, and Hydraulic Laboratories of General Directorate of State Water Works of Republic of Turkey (DSI). Since the 1987 edition of *Design of Small Dams* is the recent one, equation (1) has been repealed and a new method of computing the spillway discharge through partially-opened radial gates is valid now, which is equation (3) here. Therefore, more emphasis is given to evaluation of the discharge coefficient of equation (3), denoted by *C-87* here, using measured data of 22 different model studies performed by the mentioned organizations.

Computation of discharge over ogee spillways has been investigated by various researchers [e.g. 8, 9, 10, 11, 12]. There are other methods for computing discharge through partially-opened gates. For example, Ansar and Chen [13] presented generalized equations for discharge over ogee spillways with sharp-edged sluice gates using the data measured at many canal control structures in South Florida. Bahajantri et al [14] proposed a numerical method based on finite element approach. Saunders et al [15] developed a method using the Smoothed Particle Hydrodynamics model. Schohl [16] used the data measured on six laboratory models whose spillways had downstream face profiles defined by the method of Tennessee Valley Authority (TVA). Schohl [16] computed the discharge coefficient of the equation used by TVA, which is different from both equations (1) and (3), with many different gate openings and water surface elevations using all of the data in these six spillway model studies and noticed that they were not in close harmony. Schohl [16] additionally plotted the discharge coefficients of the TVA equation against the angle ϴ of the method of *Design of Small Dams* [2] in a figure which also showed a fairly wide scatter. Haug [17] computed the discharge coefficients of equation (3) using the laboratory model data on the radial-gated ogee spillways of five dams in the USA. The laboratory models were repeated twice with different scales for two of these dams, 1:48 and a larger scale for Hells Canyon Dam spillway model, and 1:50 and 1:120 for Wanapum Dam spillway model. The relationships of the *C* coefficient of equation (3) as a function of the angle ϴ computed by Haug [17] using all measured data of these cases in the same figure also revealed a fairly wide scatter and not a close cluster around the curve in Figure 9-31 of *Design of Small Dams* [2].

The reason for avoiding the usage of the method in the recent edition of *Design of Small Dams* [2] is most probably because it is analytically more difficult to apply than the method in its previous edition [1]. The difficulty is caused by (1) trigonometric complexity for computation of the angle ϴ and (2) geometrical hardship for *D*, which is the smallest distance between the gate lip and the surface of the ogee profile. A method for computation of both ϴ and *D* is given in the technical report: *Hydraulic Design Criteria, Sheets 311-1 to 311-5* [7], which involves a cumbersome path necessitating two tables, the first one having 20 columns and the second one 15 columns, plus a log-log graph having two lines, one for the analytical expression of the crest curve of the ogee profile and the other for its derivative. An alternative method, which computes both ϴ and *D* by a more concise numerical scheme having no need for any table or any graph, is presented by Haktanir et al [18].

The first objective of this study is to compute the discharge coefficients of the formulas for the partially-opened radial-gated ogee spillways given in the previous and recent editions of *Design of Small Dams* [1, 2] for a few dams for which the laboratory model data are available and to compare such obtained coefficients with the ones given in the pertinent figures in those books. Finally, it is aimed that a new equation be developed for the *C* coefficient of equation (3), *C-87*, using the measured data available in these laboratory reports.

2. THE DATA USED IN THE STUDY

We have searched through the web sites of the Hydraulic Investigation and Laboratories Services of USBR and the Waterways Experimentation Station of USACE and we have found many relevant reports dated as early as 1949 and as recent as 2014. We have officially applied for permission for usage of the numerical data contained in those reports separately to the concerned bureaus of both USBR and USACE. And, we have received replies from USBR and USACE stating: “You are welcome to use and translate the material as long as you provide credit to the Bureau of Reclamation and include a disclaimer that states: ‘The Bureau of Reclamation is not responsible for the accuracy of this translation.’”, and: “All government work and images that are in the public domain need no permission to use. We just ask that they are attributed correctly to the source.”, respectively. We are grateful to both USBR and USACE. We have also acquired similar consensus from DSI.

Although we have downloaded quite a few USBR and USACE reports containing hydraulic models of radial-gated spillways, unfortunately we have not been able to use some of them because (1) some crucial data like elevation of the gate trunnion were missing which were not possible to extract from scaled figures, and (2) some of the spillways did not have ogee profiles. Altogether, we have been able to collect 22 reports, six from USBR, nine from USACE, and seven from DSI, respectively [19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40]. Hence, altogether, we have been able to collect measured data for 22 different radial-gated ogee spillways. 21 of these are of laboratory model studies, and one contains data consisting of five different discharges measured in the approach channel of Seyhan Dam for various gate openings in Turkey in the year 1959 [34]. Five data triplets of lake water surface elevation, gate opening, and discharge at the actual spillway of Seyhan Dam were measured during a high incoming water period which happened in the first two weeks of the month of February in the year 1959 [34]. Each of these five discharges were determined by integration of small area flows computed by multiplying the point velocities measured with the help of a current meter at many points in the cross-section of the approach channel which was 12 meters upstream from the nose of the piers. The coordinates of the measurement points were away from each other 1.0 meter vertically and 4.3 meters horizontally [34].

All of the needed numerical data are taken from these reports by double checking. Table 1 presents some introductory information about these reports. The relevant numerical data of all of these 22 cases are presented in the M.Sc. thesis of Khalaf [41], which can be reached in the web site for theses of graduate studies of Council of Higher Education of Republic of Turkey, which is: tez.yok.gov.tr/ulusaltezmerkezi/

3. DISCHARGE COEFFICIENTS FOR RADIAL-GATED OGEE SPILLWAYS BY MEASURED DATA AND BY 1973 AND 1987 EDITIONS OF *DESIGN OF SMALL DAMS*

If all of the other terms in either equation (1) or equation (3) can be computed using the measured data, then the C coefficient remains as the only unknown. Hence, the discharge coefficient denoted by *C-73* here is computed by equation (1) leaving C alone at one side, and the discharge coefficient denoted by *C-87* here is computed by equation (3) again taking C alone to one side. The relative difference of any one of the two C coefficients taken out of the relevant charts in either the previous or the latest edition of *Design of Small Dams* [1, 2] from the C coefficient determined by either equation (1) or equation (3) using the measured data is computed by:

$$\mathrm{RD}_C = (C_{\mathrm{chart}} - C_{\mathrm{measured}}) \div C_{\mathrm{measured}} \tag{4}$$

where, C_{chart} is the coefficient taken from the relevant chart in either the 1973 or the 1987 edition of *Design of Small Dams* [1, 2], and C_{measured} is the coefficient computed using the measured data.

Table 1 - List of the dams whose laboratory reports are used in this study

	Name	Stream	Country	Organization	Scale of the model
1	Boysen	Bighorn	USA	USBR	1:48
2	Norton	Missouri	USA	USBR	1:42
3	Glen Elder	Solomon	USA	USBR	1:72
4	Toa Vaca	Toa Vaca	USA	USBR	1:48
5	McPhee	Dolores	USA	USBR	1:36
6	Folsom	American	USA	USBR	1:36
7	Kaysinger Bluff	Osage	USA	USACE	1:60
8	Oakley	Sangamon	USA	USACE	1:60
9	Oakley (Revised)	Sangamon	USA	USACE	1:60
10	Burnsville	Ohio	USA	USACE	1:40
11	Tombigbee A	Tombigbee	USA	USACE	1:15
12	Tombigbee B	Tombigbee	USA	USACE	1:25
13	Cooper	Sulphur	USA	USACE	1:36
14	Bloomington	Potomac	USA	USACE	1:60
15	Lake Darling	Souris	USA	USACE	1:36
16	Kigi	Perisuyu	Turkey	DSI	1:60
17	Yedigoze	Seyhan	Turkey	DSI	1:70
18	Kavsak	Zamanti	Turkey	DSI	1:50

Table 1 - List of the dams whose laboratory reports are used in this study (continue)

	Name	Stream	Country	Organization	Scale of the model
19	Beyhan-1	Murat	Turkey	DSI	1:70
20	Incir	Buyuk	Turkey	DSI	1:50
21	Yusufeli	Coruh	Turkey	DSI	1:40
22	Seyhan	Seyhan	Turkey	DSI	1:1 (actual dam, not the model)

4. RESULTS AND DISCUSSIONS

In those 22 reports whose data are analyzed in this study, the dams had ogee spillways with radial-gates, and we have used all of the data measured for various partial gate openings and for various lake water surface elevations. Out of these 22 cases, we are presenting the results of the spillways of Norton Dam and of the Cooper Dam in USA in this paper here. The reasons for this are manifold. First of all, the data of the Norton Dam contains many more points than those of the other reports. Secondly, its results seem to be more consistent. Thirdly, its results are in parallel to the chart in Figure 257 of the previous edition of *Design of Small Dams* [1] and to some degree to the chart in Figure 9-31 of the recent edition of *Design of Small Dams* [2]. Fourthly, the *C-87* coefficient shows a positive relationship with the ratio d/H_1. This is another result of our study that the *C-87* coefficient depends not only on the angle Θ but also on the ratio d/H_1, which is noticed for the first time by our study. The first reason for presenting the results of the spillway of the Cooper Dam is because both the experimentally observed relationships for the *C-73* and *C-87* coefficients exhibit tendencies contradicting the charts in the mentioned figures of the previous and recent editions of *Design of Small Dams* [1, 2]. The second reason is that the *C-87* coefficient shows a negative relationship with the ratio d/H_1. All of the data and the results both in numerical and graphical forms are given in the M. Sc. Thesis of Mohammed Khalaf [41], which can be reached in the web site for theses of graduate studies of Council of Higher Education of Republic of Turkey, which is: tez.yok.gov.tr/ulusaltezmerkezi/

Table 2.a gives the data for the spillway of Norton Dam taken from the report: *Hydraulic Model Studies on Norton Dam Spillway, Missouri River Basin Project, Kansas* [20] needed by the computer program coded for this study which computes the discharge coefficients for the partially-opened radial gates first by equation (1), *C-73*, and next by equation (3), *C-87*. Table 2.b presents the output of the mentioned computer program using the data given in Table 2.a as the input. The data presented in Table 2.a are necessary to compute both *C-73* and *C-87* for various combinations of gate openings (*d*'s) and lake water surface elevations (WSE's); and therefore, they are included here for anyone interested in these computations and wishing to verify the results given in Table 2.b.

For the spillway of Norton Dam, Figure 4 shows the plots of the experimentally obtained points of *C-87* against the angle Θ together with the points of *C-87* given by Figure 9-31 of the 1987 edition of *Design of Small Dams* [2]. Figure 5.a shows the plots of the experimentally obtained points of *C-73* against d/H_1 together with the points of *C-73* given by Figure 257 of the 1973 edition of *Design of Small Dams* [1], and Figure 5.b shows the plots of the experimentally obtained points of *C-87* against d/H_1. As another example, Figures 6, 7.a, and 7.b show the same relationships for the spillway of Cooper Dam as those of Figures 4, 5.a, and 5.b, respectively. Similar figures of the other 20 dams are given in the M. Sc. thesis of Khalaf [41]. In the parts following Figure 7.b, the analyses of these triplet figures of all of the 22 dams are summarized and discussed.

Table 2.a - The data for computing both of the discharge coefficients of C-73 and C-87 for the radial-gated ogee spillway of Norton Dam taken from its laboratory model report by USBR [20]

Net spillway length (L): 90.0 ft, sill height of spillway: 11 ft,
angle with vertical of the upstream face of spillway: 45º ,
elevation difference between upstream and downstream toes of spillway: 1.0 ft,
spillway apex elevation: 2296.0 ft, spillway design head (Hd): 44.7 ft,
number of piers on the spillway (N_p): 3,
abutment contraction coefficient (k_p): 0.1, piers contraction coefficient (k_a): 0.01,
radius of the radial gate (Rg): 45.0 ft,
radius of the first circle of the spillway crest profile upstream of the apex (R_1): 20.1 ft,
K and n coefficients of the downstream crest (ogee) curve: 0.52, 1.75,
elevation of the gate trunnion center: 2328.0 ft,
elevations of gate seat and top of gate at closed position: 2295.65 ft, 2332.0 ft
Spillway discharges and water surface elevations for the partial gate openings:

d (ft)	Q (cfs)	WSE (ft)
2	3000	2304
2	3900	2308
2	4800	2312
2	5300	2316
2	5900	2320
2	6300	2324
2	6900	2328
2	7100	2332
4	6600	2308
4	8000	2312
4	9200	2316
4	10500	2320
4	11500	2324
4	12200	2328
4	13000	2332
6	9000	2308
6	11000	2312
6	12800	2316

6	14500	2320
6	15800	2324
6	17100	2328
6	18200	2332
6	19500	2336
8	13500	2312
8	16100	2316
8	18200	2320
8	20100	2324
8	21800	2328
8	23400	2332
8	24900	2336
10	18900	2316
10	21700	2320
10	24000	2324
10	26400	2328
10	28800	2332
10	30500	2336
10	32100	2340
12	21500	2316
12	24700	2320
12	27900	2324
12	30600	2328
12	33000	2332
12	35500	2336
12	37600	2340
14	24000	2316
14	27900	2320
14	31400	2324
14	34500	2328
14	37600	2332
14	40500	2336
14	43000	2340
16	30500	2320
16	34500	2324
16	38400	2328
16	41800	2332
16	45000	2336
16	48000	2340
18	33000	2320
18	37800	2324

18	42000	2328
18	46000	2332
18	49500	2336
18	52800	2340
20	40300	2324
20	44800	2328
20	49200	2332
20	53000	2336
20	57500	2340
22	47800	2328
22	52600	2332
22	57100	2336
22	61600	2340
24	50500	2328
24	55800	2332
24	60700	2336
24	65400	2340
26	58800	2332
26	64000	2336
26	69000	2340
28	61500	2332
28	67200	2336
28	72800	2340
30	70300	2336
30	76100	2340
32	73400	2336
32	79800	2340
34	82800	2340

Table 2.b - Output of the computer program for the discharge coefficients for the partially-opened gates (1) by the 1973 edition and (2) by the 1987 edition of Design of Small Dams [1, 2] using the laboratory model data of the spillway of Norton Dam [20]

All lengths are in ft and discharges are in cfs
Gate trunnion coordinates (y, x): 32.00 35.35
Gate seat coordinates (y, x): -0.35 4.07
Discharge coefficients and their relative differences for
the partially-opened flow case:

Hmsrd	dmsrd	Qmsrd	C-73	Cexp-73	RD-C-73	C-87	Cexp-87	RD-C-87
8.07	2.	3000.	.6927	.7621	-9%	.6690	.7538	-11%
12.07	2.	3900.	.7025	.7934	-11%	.6690	.7825	-15%

16.07	2.	4800.	.7076	.8395	-16%	.6690	.8250	-19%
20.07	2.	5300.	.7117	.8267	-14%	.6690	.8096	-17%
24.07	2.	5900.	.7155	.8396	-15%	.6690	.8193	-18%
28.07	2.	6300.	.7190	.8306	-13%	.6690	.8075	-17%
32.07	2.	6900.	.7222	.8521	-15%	.6690	.8255	-19%
36.07	2.	7100.	.7250	.8283	-12%	.6690	.7995	-16%
12.00	4.	6600.	.6845	.7315	-6%	.6693	.7226	-7%
16.00	4.	8000.	.6934	.7515	-8%	.6693	.7402	-10%
20.00	4.	9200.	.6987	.7647	-9%	.6693	.7507	-11%
24.00	4.	10500.	.7031	.7921	-11%	.6693	.7750	-14%
28.00	4.	11500.	.7059	.8009	-12%	.6693	.7808	-14%
32.00	4.	12200.	.7082	.7938	-11%	.6693	.7711	-13%
36.00	4.	13000.	.7103	.7974	-11%	.6693	.7719	-13%
12.03	6.	9000.	.6666	.6994	-5%	.6719	.6878	-2%
16.03	6.	11000.	.6799	.7122	-5%	.6719	.6996	-4%
20.03	6.	12800.	.6879	.7268	-5%	.6719	.7120	-6%
24.03	6.	14500.	.6933	.7432	-7%	.6719	.7257	-7%
28.03	6.	15800.	.6971	.7447	-6%	.6719	.7248	-7%
32.03	6.	17100.	.7000	.7510	-7%	.6719	.7284	-8%
36.03	6.	18200.	.7030	.7520	-7%	.6719	.7267	-8%
40.03	6.	19500.	.7050	.7637	-8%	.6719	.7354	-9%
16.09	8.	13500.	.6664	.6784	-2%	.6744	.6625	2%
20.09	8.	16100.	.6771	.7021	-4%	.6744	.6846	-1%
24.09	8.	18200.	.6842	.7119	-4%	.6744	.6924	-3%
28.09	8.	20100.	.6893	.7201	-4%	.6744	.6982	-3%
32.09	8.	21800.	.6931	.7256	-4%	.6744	.7011	-4%
36.09	8.	23400.	.6961	.7312	-5%	.6744	.7041	-4%
40.09	8.	24900.	.6985	.7362	-5%	.6744	.7064	-5%
20.17	10.	18900.	.6663	.6781	-2%	.6773	.6574	3%
24.17	10.	21700.	.6752	.6934	-3%	.6773	.6710	1%
28.17	10.	24000.	.6816	.6992	-3%	.6773	.6748	0%
32.17	10.	26400.	.6863	.7122	-4%	.6773	.6853	-1%
36.17	10.	28800.	.6901	.7277	-5%	.6773	.6978	-3%
40.17	10.	30500.	.6930	.7279	-5%	.6773	.6956	-3%
44.17	10.	32100.	.6955	.7284	-5%	.6773	.6936	-2%
20.24	12.	21500.	.6556	.6647	-1%	.6803	.6401	6%
24.24	12.	24700.	.6662	.6744	-1%	.6803	.6491	5%

28.24	12.	27900.	.6738	.6908	-2%	.6803	.6636	3%
32.24	12.	30600.	.6796	.6991	-3%	.6803	.6698	2%
36.24	12.	33000.	.6840	.7043	-3%	.6803	.6726	1%
40.24	12.	35500.	.6876	.7142	-4%	.6803	.6798	0%
44.24	12.	37600.	.6905	.7181	-4%	.6803	.6812	0%
20.29	14.	24000.	.6450	.6616	-3%	.6837	.6320	8%
24.29	14.	27900.	.6573	.6721	-2%	.6837	.6433	6%
28.29	14.	31400.	.6662	.6818	-2%	.6837	.6519	5%
32.29	14.	34500.	.6729	.6884	-2%	.6837	.6569	4%
36.29	14.	37600.	.6781	.6988	-3%	.6837	.6649	3%
40.29	14.	40500.	.6822	.7081	-4%	.6837	.6716	2%
44.29	14.	43000.	.6856	.7125	-4%	.6837	.6736	2%
24.34	16.	30500.	.6485	.6644	-2%	.6877	.6321	9%
28.34	16.	34500.	.6586	.6725	-2%	.6877	.6402	7%
32.34	16.	38400.	.6662	.6848	-3%	.6877	.6509	6%
36.34	16.	41800.	.6721	.6921	-3%	.6877	.6563	5%
40.34	16.	45000.	.6769	.6992	-3%	.6877	.6612	4%
44.34	16.	48000.	.6808	.7055	-4%	.6877	.6651	3%
24.37	18.	33000.	.6397	.6632	-4%	.6919	.6267	10%
28.37	18.	37800.	.6510	.6739	-3%	.6919	.6386	8%
32.37	18.	42000.	.6596	.6814	-3%	.6919	.6455	7%
36.37	18.	46000.	.6662	.6904	-4%	.6919	.6529	6%
40.37	18.	49500.	.6715	.6954	-3%	.6919	.6559	5%
44.37	18.	52800.	.6759	.7004	-3%	.6919	.6587	5%
28.39	20.	40300.	.6435	.6674	-4%	.6966	.6292	11%
32.39	20.	44800.	.6530	.6709	-3%	.6966	.6333	10%
36.39	20.	49200.	.6603	.6789	-3%	.6966	.6402	9%
40.39	20.	53000.	.6662	.6825	-2%	.6966	.6424	8%
44.39	20.	57500.	.6711	.6976	-4%	.6966	.6549	6%
32.40	22.	47800.	.6464	.6689	-3%	.7022	.6291	12%
36.40	22.	52600.	.6545	.6750	-3%	.7022	.6350	11%
40.40	22.	57100.	.6610	.6817	-3%	.7022	.6403	10%
44.40	22.	61600.	.6663	.6912	-4%	.7022	.6479	8%
32.40	24.	50500.	.6398	.6673	-4%	.7074	.6251	13%
36.40	24.	55800.	.6486	.6726	-4%	.7074	.6310	12%
40.40	24.	60700.	.6557	.6782	-3%	.7074	.6359	11%
44.40	24.	65400.	.6615	.6850	-3%	.7074	.6411	10%

36.39	26.	58800.	.6428	.6715	-4%	.7128	.6281	13%
40.39	26.	64000.	.6504	.6746	-4%	.7128	.6314	13%
44.39	26.	69000.	.6567	.6799	-3%	.7128	.6356	12%
36.38	28.	61500.	.6369	.6707	-5%	.7187	.6251	15%
40.38	28.	67200.	.6452	.6732	-4%	.7187	.6288	14%
44.38	28.	72800.	.6519	.6794	-4%	.7187	.6344	13%
40.36	30.	70300.	.6399	.6736	-5%	.7245	.6277	15%
44.36	30.	76100.	.6471	.6768	-4%	.7245	.6312	15%
40.34	32.	73400.	.6346	.6769	-6%	.7300	.6288	16%
44.34	32.	79800.	.6423	.6802	-6%	.7300	.6332	15%
44.31	34.	82800.	.6375	.6798	-6%	.7350	.6315	16%

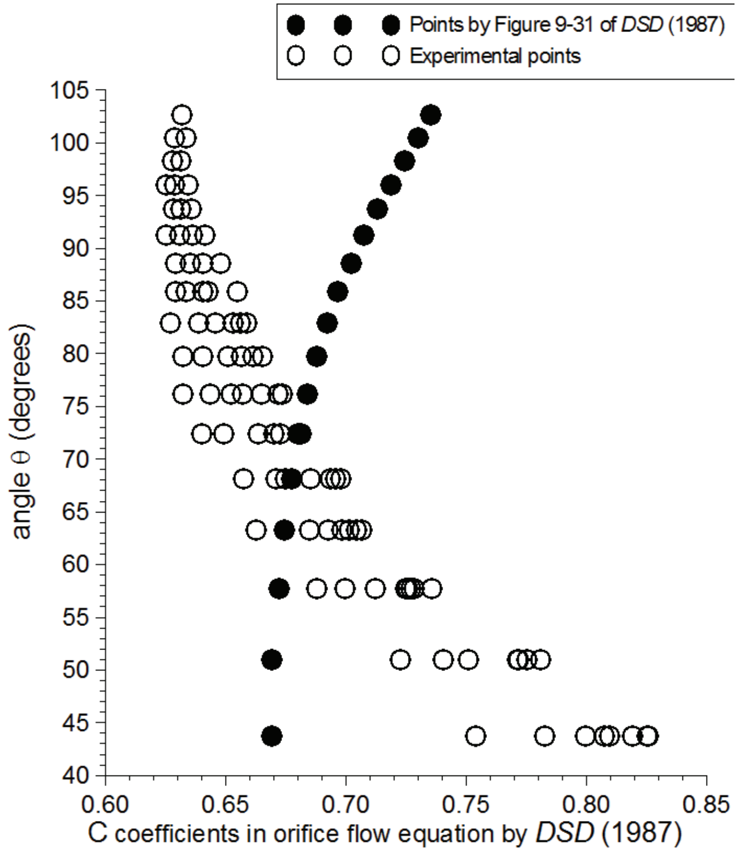

Figure 4 - Plot of the discharge coefficients C-87 against the angle Θ obtained by the data measured on the laboratory model of the spillway of Norton Dam [20] together with the points given by Figure 9-31 of the third edition of Design of Small Dams [2] for the same Θ's

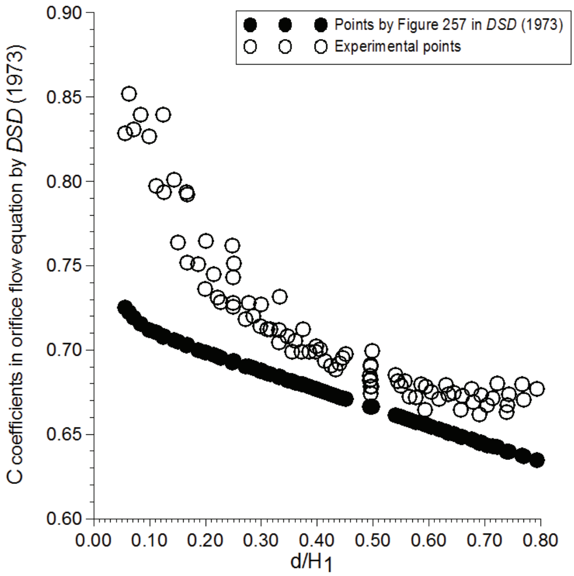

Figure 5.a - Plot of the discharge coefficients C-73 against the ratio d/H_1 obtained by the data measured on the laboratory model of the spillway of Norton Dam [20] together with the points given by Figure 257 of the second edition of Design of Small Dams [1]

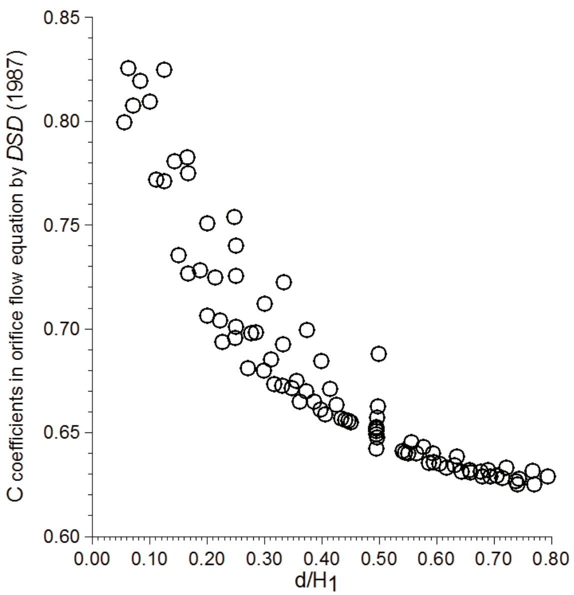

Figure 5.b - Plot of the discharge coefficients C-87 against the ratio d/H1 obtained by the data measured on the laboratory model of the spillway of Norton Dam [20]

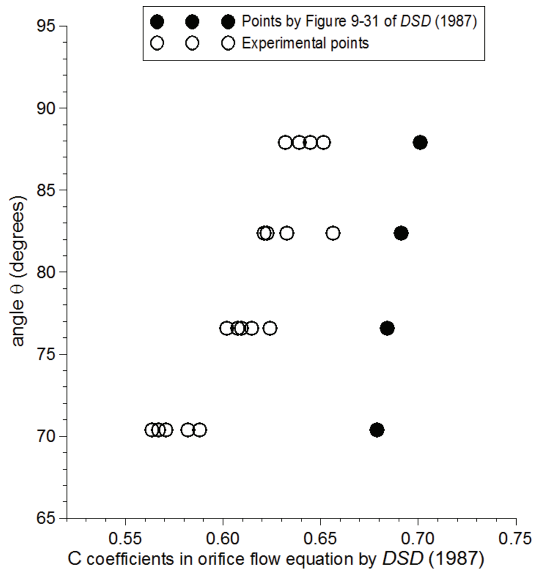

Figure 6 - Plot of the discharge coefficients C-87 against the angle Θ obtained by the data measured on the laboratory model of the spillway of Cooper Dam [30] together with the points given by Figure 9-31 of the third edition of Design of Small Dams [2] for the same Θ's

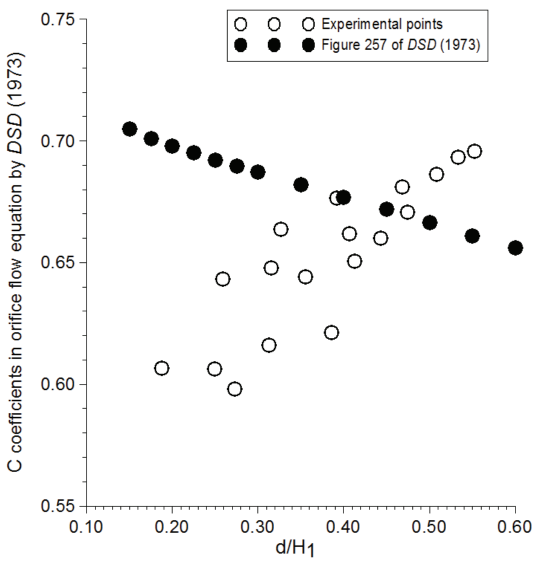

Figure 7.a - Plot of the discharge coefficients C-73 against the ratio d/H_1 obtained by the data measured on the laboratory model of the spillway of Cooper Dam [30] together with the theoretical points given by Figure 257 of the second edition of Design of Small Dams [2]

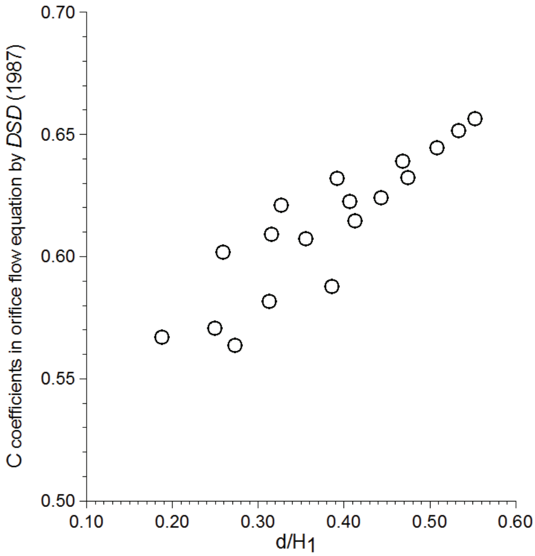

Figure 7.b - Plot of the discharge coefficients C-87 against the ratio d/H_1 obtained by the data measured on the laboratory model of the spillway of Cooper Dam [30]

First of all, we have noticed that a few different-magnitude *C-87*'s exist against the same numerical value of the angle Θ, which can be clearly seen in both Figures 4 and 6. It is a geometrical fact that the angle Θ assumes a constant value when the gate opening is fixed, because the tangents to the gate lip and to the crest curve of the spillway will be at fixed positions in that case. Therefore, it is obvious that there being different magnitudes of the *C-87* coefficient corresponding to the same value of the angle Θ means that *C-87* depends on another independent variable together with Θ. Yet again, it is analytically evident that the other explanatory variable must be related to the lake water surface elevation simply because the other *C-87*'s for the same Θ correspond to different water surface elevations at the same gate opening position. Therefore, the other explanatory variable is deemed to be the ratio of the vertical gate opening to the total head with respect to the spillway apex, which is symbolized by d/H_1. In the 1973 edition of *Design of Small Dams* [1], the discharge coefficient *C-73* is determined as a function of d/H_1. Similary, the analyses in our study indicate that the discharge coefficient of the new method, *C-87*, should be a function of d/H_1 together with the angle Θ. Figures of pairs of both Figures 5.a, 5.b, and 6.a, 6.b reveal plots verifying this so-far-ignored fact. Figure 5.a shows the variation of the measured values of the *C-73* coefficient together with the values given by Figure 257 of the 1973 edition of *Design of Small Dams* [1] for the spillway of Norton Dam. Although there is not a close fit, still, the measured *C-73*'s exhibit parallel values to those given by Figure 257 of the 1973 edition of *Design of Small Dams* [1]. Interestingly, the plots of the measured *C-87* values against d/H_1 also exhibit a trend parallel to the measured *C-73* values. In other words, as can be appreciated easily by inspecting Figure 5.b, although unnoticed so far, the discharge coefficient of the 1987 method, *C-87*, also indicates a close relationship to the ratio d/H_1. The measured data of the spillway of Norton Dam is one of a total of 22 such reports we have been able to obtain. In Figure 7.a, an interesting relationship is observed between the discharge coefficient of the previous method, *C-73*, and the ratio d/H_1, which is contradictory to the theoretical curve. So, for the spillway of Cooper Dam, the relationship between *C-73* and d/H_1 is opposite of what is expected according to Figure 257 of the 1973 edition of *Design of Small Dams* [1]. Yet, as seen in Figure 7.b, for Cooper Dam the relationship between the discharge coefficient of the recent method, *C-87*, and the ratio d/H_1 also exhibits an increasing *C-87* with an increasing d/H_1, parallel to the relationship of *C-73* with d/H_1.

In short, out of 22 reports, 9 cases revealed *C-73* and d/H_1 and also *C-87* and d/H_1 relationships parallel to the curve given in Figure 257 of the 1973 edition of *Design of Small Dams* [1], which is decreasing *C-73* with increasing d/H_1 and also decreasing *C-87* with increasing d/H_1, and 13 cases showed contradictory behavior, namely, increasing *C-73* with increasing d/H_1 and also increasing *C-87* with increasing d/H_1. The reason for the relationship between *C-87* and d/H_1 having a negative slope for some spillways and a positive slope for some other spillways must be related to the dimensions of the spillway and of the gates. Therefore, we have computed many ratios of dimensions, which are: (sill height)/(spillway length), (trunnion height)/(spillway length), (trunnion height)/(sill height), (design head)/(spillway length), (design head)/(sill height), (gate height)/(spillway length), (gate height)/(sill height), and (radius of gate)/(spillway length), which are symbolized as P/L, T_H/L, T_H/P, H_d/L, H_d/P, G_H/L, G_H/P, Rg/L, respectively, with the expectation of relating the behavior of positive or negative slope for the relationship of *C-87* against d/H_1 to a tangible dimensionless quantity. Trunnion height, T_H, is the difference in elevations of the gate trunnion and of the gate seat, sill height (P) is the difference of elevations of the spillway apex and bottom of the approach channel at the upstream toe of the spillway, design head (H_d) is the net head over the spillway apex for the design discharge, gate height (G_H) is the difference of elevations of the top and bottom lips of the gate in closed position, and radius of gate (Rg) is the outer radius of the gate. Tables 3.a and 3.b present these ratios for all of the 22 cases, the former having those spillways with negative slope for the *C-87* against $d/H1$ relationship and the latter with positive slope. Investigation of these tables suggests that the ratios of (trunnion height)/(spillway length) and/or (radius of gate)/(spillway length) can be taken as guides for the slope of the relationship between *C-87* and the second explanatory variable d/H_1. As the outcome of the analyses, whose summaries are given in Tables3.a and 3.b, it can be said that the slope of the relationship between *C-87* and d/H_1 is negative when $T_H/L > 0.25$ and positive if $T_H/L < 0.25$. Aside from that, the slope of this relationship is negative when $Rg/L > 0.5$ and positive if $Rg/L < 0.5$.

Leaving these observations aside, we have plotted the *C-87* coefficients against the angle Θ obtained by the measured data of all of these 22 spillways all in one figure, which is Figure 8. Six of these 22 spillways have gate seats directly at the top of the apex, while the gate seats of the other 16 are placed downstream from the apex at a distance about a small percentage of the design head. Because the trajectories of the shooting jet under the partially-opened radial gate by these two distinct cases should be different, the relationship of *C-87* with the angle Θ is also deemed to be different; and hence, although not too far apart, there are two different charts for these two cases [2, 7]. In Figure 8, those charts from Figure 9-31 of *Design of Small Dams* [2] are shown by green and yellow lines extended within the same ranges as in Figure 9-31. The points of *C-87* against Θ are shown in blue for those spillways whose gate seats are downstream from the apex, and the points of *C-87* against Θ are shown in red for those spillways whose gate seats are right on top of the apex in Figure 8. First of all, the overall appearance of the plotted points in Figure 8 does not give hope for a generalizable clustering around a potential curve, and we come to the conclusion that a generalized model for the discharge coefficient *C-87* does not look to be meaningfully unique. Another noteworthy observation in Figure 8 is that, the end points of the green and yellow lines in the figure, which are taken from Figure 9-31 of *Design of Small Dams* [2], are actually too short to cover the experimentally measured ranges.

Table 3.a - Various ratios pertaining to some spillway and gate dimensions for those dams for which the discharge coefficient C-87 exhibits a decreasing relationship with increasing d/H_1

Dam	L	P	$\frac{P}{L}$	$\frac{T_H}{L}$	$\frac{T_H}{P}$	$\frac{H_d}{L}$	$\frac{H_d}{P}$	$\frac{G_H}{L}$	$\frac{G_H}{P}$	$\frac{Rg}{L}$
Boysen	60 ft	10 ft	0.17	0.35	2.1	0.9	5.2	0.42	2.5	0.70
Mcphee	56 ft	8 ft	0.14	0.28	2.0	0.6	3.9	0.50	3.5	0.50
Norton	90 ft	11 ft	0.12	0.36	3.0	0.5	4.1	0.40	3.3	0.50
Toa Vaca	90 ft	13 ft	0.14	0.33	2.3	0.4	3.1	0.38	2.6	0.46
Bloomington	210 ft	13 ft	0.06	0.06	1.0	0.2	3.1	0.15	2.5	0.17
Yusufeli	57.5 m	11.7 m	0.20	0.11	0.5	0.2	1.1	0.15	0.8	0.22
Kigi	28 m	4 m	0.14	0.25	1.8	0.4	3.1	0.40	2.8	0.60
Yedigoze	66 m	4 m	0.06	0.11	1.7	0.3	4.2	0.28	4.7	0.25
Kavsak	37.8 m	10 m	0.26	0.22	0.8	0.6	2.1	0.70	2.6	0.47

Table 3.b - Various ratios pertaining to some spillway and gate dimensions for those dams for which the discharge coefficient C-87 exhibits an increasing relationship with increasing d/H_1

Dam	L	P	$\frac{P}{L}$	$\frac{T_H}{L}$	$\frac{T_H}{P}$	$\frac{H_d}{L}$	$\frac{H_d}{P}$	$\frac{G_H}{L}$	$\frac{G_H}{P}$	$\frac{Rg}{L}$
Burnsville	126 ft	37 ft	0.30	0.14	0.47	0.33	1.1	0.28	0.9	0.27
Cooper	200 ft	28.2 ft	0.14	0.04	0.25	0.13	0.9	0.11	0.8	0.11
Glen Elder	600 ft	9.5 ft	0.02	0.03	1.74	0.04	2.7	0.04	2.3	0.04
Lake Darling	215 ft	12.5 ft	0.06	0.03	0.64	0.12	2.0	0.10	1.8	0.11
Oakley	168 ft	18 ft	0.11	0.06	0.58	0.22	2.0	0.16	1.5	0.20
Oakley (Rvsd)	160 ft	11 ft	0.07	0.09	1.35	0.18	2.7	0.15	2.2	0.16
Folsom	210 ft	154 ft	0.73	0.07	0.10	0.30	0.4	0.25	0.3	0.21
Kaysinger	160 ft	58.3 ft	0.36	0.10	0.28	0.27	0.7	0.30	0.8	0.30
Tombigbee A	104 ft	5 ft	0.05	0.03	0.55	0.14	3.0	0.07	1.6	0.20
Tombigbee B	495 ft	5 ft	0.01	0.01	1.40	0.04	3.7	0.03	3.0	0.04
Incir	21.8 m	3 m	0.14	0.26	1.94	0.53	3.8	0.36	2.7	0.50
Seyhan	42 m	2 m	0.05	0.08	1.75	0.28	6.0	0.14	3.1	0.21
Beyhan-1	69 m	5 m	0.07	0.13	1.76	0.26	3.6	0.24	3.4	0.23

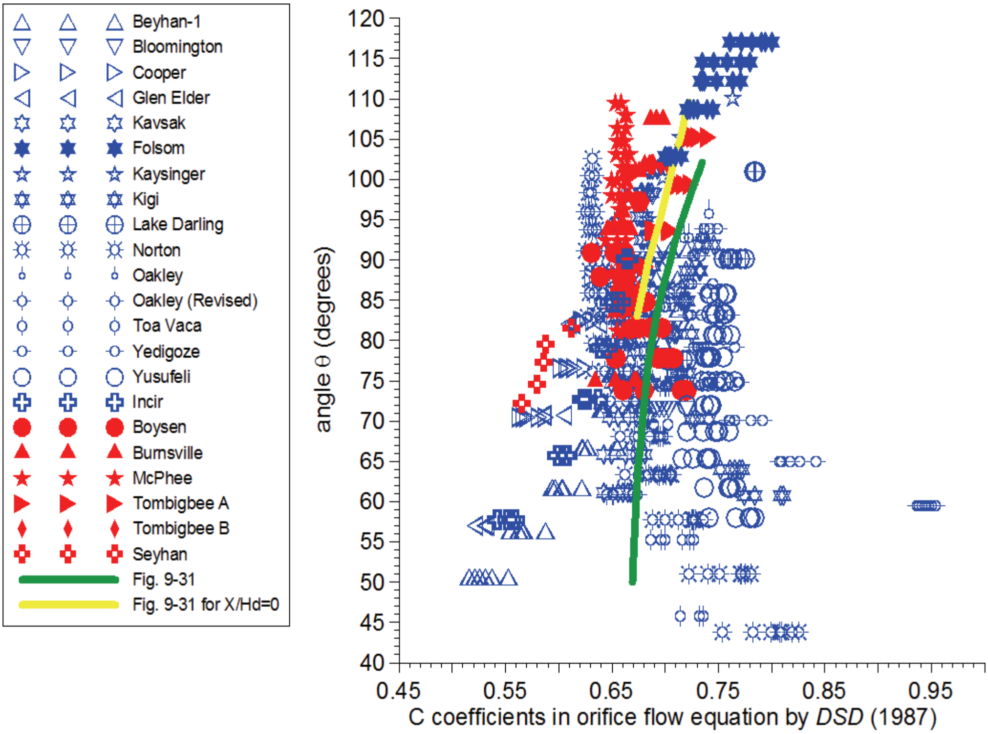

Figure 8 - Plot of the discharge coefficients C-87 against the angle Θ obtained by the measured data in all of 22 reports used in this study together with the charts given in Figure 9-31 of the third edition of 'Design of Small Dams' [2]

The scales of those laboratory models vary between 1:15 to 1:72, eight with scales greater than 1:60, four with scales 1:48 and 1:50, seven within scales 1:36 and 1:42, and two having the scales of 1:15 and 1:25. Seyhan Dam's spillway has a scale 1:1. And hence, there should be scale effects on the measured values. As noted by Haug [17], for small gate openings, surface tension and viscosity effects may be significant which may have affected the hydraulic behavior of the spilling jet for small-scale models. Haug [17] commented: "Scale models smaller than 1/50 can have more than 15 % error just due to viscous scale effects." The scales of the spillway models of Yedigoze and Beyhan-1 Dams are 1:70 and that of Glen Elder Dam is 1:72 [36, 38, 21], which are the smallest size models out of the 22 cases analyzed in our study. For these three spillway models, the plotted points with small Θ angles, meaning small gate openings, look appreciably deviant from those of larger openings in Figure 8 and in the individually drawn figures [41]. Looking at Figure 3 above, which contains the original form of the diagram given in Figure 9-31 in the recent edition of *Design of Small Dams* [2], it can be observed that the plotted points of *C-87* against Θ measured on the spillways of five cases only also show a fairly wide scatter around the averaging curve for angles smaller than 72°. In short, we believe it is difficult to expect close clustering of relationships obtained out of laboratory measurements from different scale models.

Yet, there are geometrical properties of the approach conditions and the spillway configuration peculiar to each dam. For example, some spillways are located at either the left-hand side or the right-hand side of the embankment, and yet some others are located right in the middle of a concrete arch dam with no approach channel. The geometrical shapes of the approach channels are also different from each other. In short, even if the needed quantities affecting the discharge characteristics of a spillway were measured directly on the prototype structure, still there would be differences which would be off from a generalized relationship.

Therefore, our final result is that for an important dam, a laboratory model study, with a scale no smaller than 1:50, must be carried out beforehand, and the discharge coefficient of the analytical model had much better be individually obtained rather than using a generalized chart like Figure 9-31 of the third edition of *Design of Small Dams* [2]. Inspecting the relationships of *C-87* against Θ and against d/H_1 for each report separately implicates that indeed individually for each dam *C-87* may be significantly related to both of these explanatory variables, Θ and d/H_1. Hence, regression equations are computed separately for each one of these 22 cases analyzed in this study. Table 5 presents the magnitudes of the coefficients, of the **t** values of the coefficients, and of the determination coefficients of the regressions for the Norton and Cooper Dams. The others are given in the M.Sc. thesis by Khalaf [41], and for most of them the regression coefficients are significant at 95 % level and their determination coefficients are around 0.90.

*Table 5 - Values of the coefficients, of their **t** values (in parentheses), and of the determination coefficients (R^2, adjusted for degree of freedom) of the regression equations for C-87 for Norton and Cooper Dams*

Regression equation for *C-87* is: $C\text{-}87 = c_0 + c_1\times\Theta + c_2\times\Theta^2 + c_3\times(d/H_1) + c_4\times(d/H_1)^2$

Dam / R^2_{adj}	c_0	c_1	c_2	c_3	c_4
Norton $R^2_{adj} = 0.92$	1.12 (65.1)	-0.00888 (-15.4)	0.000052 (13.1)	-0.259 (-10.2)	0.144 (5.2)
Cooper $R^2_{adj} = 0.97$	-0.649 (-3.0)	0.0285 (5.2)	-0.000165 (-4.7)	0.127 (7.4)	0.0

During the construction of the approach channel of the spillway of a dam, a safe and sound steel rope and cable car unit can be mounted over it. As compared to the total cost of the spillway and its appurtenances, the cost of this cable car unit will be negligibly small. During days of high incoming flows, either by a conventional current meter or another instrument like an Acoustic Doppler Anemometer, point velocities all over the cross-section of the approach channel can be measured and the total discharge can be determined by integration of small area flow rates over the entire section. This experiment can be repeated for various gate openings and lake water surface elevations in any day of any year whenever suitable. The occurrences of high waters during the service life of a dam most probably will be smaller than the critical design flood. Therefore, real-life experiments will probably be carried out for fairly small gate openings and not too high lake water surface elevations. This should be an advantage actually, because at small gate openings and low water surface elevations the viscous and surface tension effects may yield unrealistic measurements for small-scale laboratory models. Hence, real-life measurements on prototype spillways would yield realistic data for low values. The actual spillway measurements at low heads and small gate openings could be conjunctively evaluated with high heads and large gate openings obtainable in laboratory models.

5. CONCLUSIONS

Technical reports of six laboratory studies by USBR, nine by USACE, six by DSI (General Directorate of State Water Works of Turkey) containing measured data for partial gate openings of radial-gated ogee spillway models are analyzed. Five points of lake water surface elevation, gate opening, and spillway discharge, which are based on actual point velocity measurements across the entire section of the approach channel of Seyhan Dam in Turkey are also included in the study. The conclusions reached are as follows.

Figure 9-31 in the recent edition of *Design of Small Dams* [2] is insufficient for accurately estimating the discharge coefficient of the equation used by USBR for computing the discharge over an ogee spillway for the case of partially-opened gates. Analyses of these 22 reports indicate that the discharge coefficient, symbolized by *C-87* here, should be calculated relating it (1) to the angle between the tangent to the gate lip and the tangent to the crest curve closest to the gate lip (Θ) and (2) to the ratio of the gate opening to the head with respect to the spillway apex (d/H_1). Figure 9-31 in *Design of Small Dams* [2] however, relates *C-87* to Θ only.

The relationship between the coefficient *C-87* as the dependent variable against both the angle Θ and the ratio d/H_1 must be determined separately for each dam by a comprehensive laboratory model study having a scale no smaller than 1:50, while a generalized curve will not yield accurate results for the (Spillway discharge) ↔ (Head) relationship for the case of the partially-opened gates for a specific dam.

Symbols

c_i : Coefficients of the regression equation relating *C-87* to d/H_1 and Θ (i = 0, 1, 2, 3, 4)

C : Coefficient of discharge in general equations for partially-opened radial-gated ogee spillways

C-73 : Symbol used in this study for coefficient of discharge in equation (1)

C-87 : Symbol used in this study for coefficient of discharge in equation (3)

C_{chart} : Magnitude of coefficient of discharge taken from the relevant chart given in either 1973 or 1987 edition of the book: *Design of Small Dams*

$C_{measured}$: Magnitude of coefficient of discharge computed by the inverse of either equation (1) or equation (3) using the measured data

d : Vertical opening of the partially-opened radial gate

g	: Acceleration of gravity
H	: Total head just upstream of the gate with respect to the spillway apex in equation (2)
H	: Total head just upstream of the gate with respect to the center of the gate opening in equation (3)
H_1, H_2	: Total heads to the bottom and top of the gate opening, respectively
k_a	: Approach abutments contraction coefficient
k_p	: Pier contraction coefficient
L	: Net length of the spillway crest excluding the piers
L_e	: Effective length of the spillway crest
N_p	: Number of piers on the spillway crest
P	: Sill height of the spillway
Q	: Discharge of water spilling over the radial-gated ogee spillway when the gates are partially-opened
R^2_{adj}	: Determination coefficient of the regression equation adjusted for degree of freedom
RDc	: Relative difference of a C coefficient taken out of the relevant chart in either 1973 or 1987 edition of the book: *Design of Small Dams* from the experimental C coefficient
Θ	: Angle between the tangent to the gate lip and the tangent to the crest curve at the point nearest to the lip

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