Effective parameters for calculating the discharge of spillway with radial gates at large dams

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Abstract

In addition to the use of spillways with radial gate with a short height at regulating dams, they are used in the body of large reservoir dams and at the lower levels for flushing the sediments or regulating the flow at the outlet. At the earth and rockfill dams, the spillway is not a part of the dam and it is provided on either of the banks of the river which results in an oblique approach flow to the spillway that likely to affect the discharge capacity of the spillway. Accordingly, in each case, the parameters affecting the discharge of gated spillway are different. Studies on the determination of the discharge of spillways with radial gates are limited to three categories: USACE (1977), USBR (1973) and Sinniger and Hager (1989). There are some complexities for estimation the discharge of spillways with radial gates, which need further studies in this field (The difference in base form of the variation of the discharge with upstream head, providing the earlier methods based on limited experimental and field verifications, the complexity of determining the required parameters for estimation the discharge in USACE (1977), ignoring the effect of gate seat location on the discharge of gated spillways in USBR (1973) and Sinniger and Hager (1989), ambiguity in accuracy of the proposed method for estimating the discharge of gated spillway for its application as the flood discharge systems in large dams). Also, there is insufficient information about the capability of proposed equations under transition flow between orifice and non-orifice conditions. This paper presents an investigation about the ability of different methods in estimating the discharge of the spillway with radial gates. For this goal, 912 data series were collected from some experimental observations on the physical models which constructed from seventeen flood discharge systems in Iranian large dams. In addition to dimensional analysis of effective parameters on the discharge of gated spillway, new relations were established for the simple determination of gate opening and gate lip angle, in contrast to the sophisticated approach used in the USACE (1977) method. In addition to assessing the effects of different parameters on the discharge of gated spillways based on F-test, a new dimensional equation was proposed for estimating the discharge of gated spillways in relation to the most important parameters. Based on all experimental data, the Mean Absolute Relative Errors (MARE) for discharge estimation from USACE (1977), USBR (1973), Sinniger and Hager (1989) and new proposed equation are 6.9%, 9.1%, 5.1% and 3.9%, respectively. Under transitional flow condition, MARE from the above methods are 13.9%, 5.4%, 22.2% and 4%, respectively. This result shows that the unanimous performance of the new proposed method under all flow conditions. Also, it is significant the accuracy of USBR (1973)'s method for discharge estimation under transitional flow condition. The results show that the difference in the shape of the downstream shape of spillway compared to the standard ogee shape, lead to MARE up to 11.8% in the earlier methods. However, the new proposed method is suitable for application in the presence of different downstream shapes of spillway. In similar conditions, the MARE for discharge estimation has decreased to 4.4% by using the new proposed method. The results show that under the simultaneous operating conditions of eight radial gates over the spillway, MARE from the previous proposed methods increased to 22.3%. In this condition, MARE from the new proposed method was about 2.9%. Experimental observations also show an increase in the MARE for discharge estimation of gated spillway up to 11% in operating conditions of only one gate from the several gates. This is due to the effect of the fatigue flow lines behind of the closed gates on the pattern of open-gate flow lines.

Keywords: Discharge, Flood Discharge System, Gated Spillway, Large Dams, Physical Modelling.

1. INTRODUCTION

The application of gates, including sluice and radial (or Tainter) gates in combination with overflow structures, would result in better management of the reservoir of the dam compared to the design of the free overflow design. The use of radial gates is more common than sluice gates, especially in the large dam, but to the ease operation and need less force for operation.

Radial gates are designed on an ogee spillway to achieve a variety of goals. In regulating dams, gated spillways with short height, are used to regulate the flow according the downstream water need or to stabilize the upstream water depth for passing the constant discharge from the upstream intakes. Also, ogee spillways with radial gates can be used in the body of large reservoir dams and at the lower levels for flushing the sediments or regulating the flow at the outlet. Figure 1 shows the use of gated spillways with radial gates as a flood discharge system at the sideway of Karkheh dam in Khuzestan province in Iran.

Figure 1- An example of the use of gated spillways with radial gates as a flood discharge system at the sideway of Karkheh dam in Khuzestan province in Iran.

By using the stage-discharge relationship, it is possible to measure the flow discharge from the reservoir. On the other hand, by using this relationship, the operator can regulate the desired gate opening to release the discharge according the downstream water needs. In spite of the extensive use of gated spillways, there are only some limited works for discharge estimation of these structures. United States Bureau of Reclamation (USBR, 1973), developed the following equation for discharge estimation of an ogee spillway with radial gate [1]:

$$Q = \frac{2}{3} C_d L \sqrt{2g} \left(H_1^{\frac{3}{2}} - H_2^{\frac{3}{2}} \right) \tag{1}$$

in which, Q =the discharge, C_d =the discharge coefficient, L=effective length of the spillway, g=acceleration due to the gravity, H_1=upstream water head over the crest, and H_2=upstream water head over the bottom of the gate (H_2=H_1-y_L, where y_L is the vertical opening of the gate against to the crest). The discharge coefficient (C_d) from this method can be determined as a function of the ratio of y_L/H_1. It should be noted that this method is developed for situations where the gate seat designed at the weir crest. Figure 2 shows the geometric parameters which affect the discharge of spillways with radial gate.

United States Army Corps of Engineers (USACE, 1977), proposed the following formula for discharge estimation of spillways with radial gates [2]:

$$Q = C_d L w \sqrt{2gH} \tag{2}$$

where w= net gate opening (the distance between the bottom edge of the gate from the crest) and H=head to center of gate opening (Figure 2). C_d is the discharge coefficient, which can be determined as a function of β and the ratio of X_S/H_D from Hydraulic Design Chart 311-1 (X_S is the distance of gate seat to the crest and H_d is the design head of the spillway) According to Figure 2, the angle (β) formed by the tangent to the gate lip and the tangent to the crest curve at the nearest point of the crest curve. The net gate opening is considered to be the shortest distance from the gate lip to the crest curve.

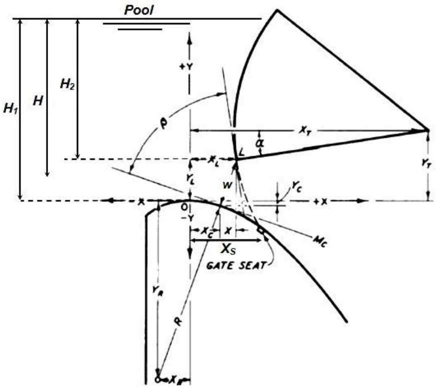

Figure 2- Defination sketch of geometric parameters for discharge estimation of spillways with radial gates

USACE (1977)'s method was developed based on limited experimental data from the three physical models and some data about field operation of three spillways with a radial gate in the United States. This relation is also based on a limited some observation in which at least three gates have been operated simultaneously on the same gate openings. Discharge coefficients for a single bay would be lower because of side contractions. In this method, it is necessary to use three Hydraulic Design Charts named as Chart 311-2, 311-3, 311-4 to determine β and *w*. It is noteworthy to mention that USACE (1977)'s method for Tainter gates mounted on spillway crests shaped to $X^{1.85} = -2H_d^{\ 0.85} \times Y$. It is believed that this method is accurate to within ±2%, for gate opening-head ratios (w/H_0) less than 0.5.

To find out the discharge coefficient of gated spillways in Equation (2), Sinniger and Hager (1989) proposed the following formula [3]:

$$C_d = 0.908\left[1 - \frac{\beta}{277^\circ}\right]\left(\frac{H}{H_d}\right)^{0.12} \tag{3}$$

Due to the difference in the level of gate seat point compared to the downstream channel, Gated spillways only operated under free flow condition, especially for its application as a flood discharge system in the vicinity of large dams. However, there are some complexities in the discharge estimation of gates spillways for above mentioned applications. Depending on the level of the edge of the gate in the opening position and upstream water level, there are three flow conditions from the gated spillways: (a) Free Non-Orifice flow, (b) Free Orifice flow and (c) Transition zone between the orifice and non-orifice flow. Hussain et al. (2014), indicated that the orifice flow condition requires head over the crest exceeds from (1.5-1.7) *w* [4]. Also, Hager and Bremen (1988) found that the flow from the spillways with sluice gate changes to non-orifice condition for $y_L/H_1>0.77$ [5]. Under orifice and non- orifice flow conditions, the discharge of gated spillways, varies with half and three second
power of upstream head, respectively. However, there has not yet been a general study about the variation of the discharge of gated spillways with upstream head under a transition between orifice and non-orifice flow conditions. Under transition zone, the flow condition is unstable and it seems that the discharge variation with upstream head is different under falling with rising. Consequently, the discharge estimation under transition zone requires further sensitivity and precision.

Due to the curvilinearity of the flow, a suction effect predominates and the flow increases for the same gate opening and reservoir level. It is economical to provide a gate slightly below crest as it reduces the cost of the spillway structures which has to conform to the shape of the jet for the orifice flow. The Ogee profile, determined for free flow condition, may be subjected to cavitation damage for orifice flow, especially for small gate opening. When the gate seat is provided slightly downstream of the crest, the cavitation problem is also reduced. Among of the previous studies for discharge estimation of gated spillways, the proposed method by USBR (1973) is presented for the design of gate seat on the crest which is not applicable in practical cases. Consequently, further studies are required for about the effect of gate seat position on the discharge estimation of gated spillways.

In the earthen and rockfill dams, the spillway is not a part of the dam and it is provided on either of the banks of the river. Thus approach flow to the spillway is oblique and that will affect the discharge capacity of the spillway. However, the effect of presence of guide walls and the curvature effect of the flow lines on the discharge coefficient of gated spillways has not been studied with the above mentioned methods and requires further study.

Due to executive considerations such as the easy operation of the gates, reduction in the required force for gate displacement, a defect in the operation system of the gate, the designers are more likely to set up a set of multipe gates. In this case, some gates may be open and some others closed. The dead zone behind the closed gates, can affect the pattern of flow lines near the open gates. This could affect the discharge estimation of gated spillways using above mentioned equations.

The previous methods only can be used for discharge estimation of gated spillways where the downstream face of the spillways follows from the ogee standard shape. Deviation from ogee standard shape can be affect the application of the previous methods for calculation of β and *w*. Consequently, some general methods are needed for the different geometrical characteristics of the spillway.

On the other hand, differences in the form of the stage-discharge relationships from Equations (1) and (2), necessitate the evaluation of the efficiency of various proposed methods for discharge estimation of gated spillways under orifice and transition flow conditions.

Table (1) shows a series of effective parameters for calculating the discharge of spillways with radial gates and its application as a flood discharge system at the vicinity of large dams.

Table 1- Effective Parameters for Calculating the Dicharge of Spillways with Radial Gates at Large Dams

Series	Parameter	Symbol	Series	Parameter	Symbol
1	Gate lip angle	β	11	Width of approach channel	B
2	Upstream weir slope	m	12	Width of gate	b
3	Upstream weir depth	H	13	Pier width	b_P
4	Discharge of each gate	Q_i	14	Pier shape	-
5	Opening of each gate	y_{Li} (i=1-N)	15	Radial distance of each gate	r
6	Viscousity	ν	16	Weir height	P
7	Surface tension	σ	17	Gate radius	R
8	Design head	H_D	18	Gate seat situation	X_S
9	Downstream weir face	-	19	Turnnion	X_T
10	Mass density	ρ	20	Turnnion height	Y_T

In this paper, totally 912 data series was used to evaluate the performance of different methods for estimating the discharge of gated spillways. The data was derived from some experimental observations on the physical models which constructed from seventeen flood discharge systems in Iranian large dams. Based on the Pi-Buckingham theory, it was presented some non-dimensional parameters which affected the discharge of gated spillways and the corresponding relationship was deduced. The capability of different methods for discharge estimation was compared under orifice and transitional flow conditions. Also, a set of theoretical equations was derived for explicit and simple determination of β and *w*. Based on F-test, a new dimensional equation was proposed for estimating the discharge of gated spillways in relation with the most important parameters.

2. Materials and Methods

In this study, an extensive set of laboratory data was used to investigate the applicability of the different previous proposed relationships and to propose a new relationship to determine the discharge of spillways with radial gate. For this purpose, the results of studies on the physical models made from the flood discharge systems as a part of the Iranian reservoir dams were used. Totally, 17 models were studied. From this set of physical models, 16 dams were constructed in Iran during the years 1992 to 2014 at the Hydraulic Laboratory of the Iranian Water Research Institute. Also, the results of a physical model of the Ostoor dam have been used in the EPFL hydraulic laboratory in Switzerland. Figure 3 shows the images of a set of physical models of the 17 flood discharge systems. Also, in Table 2, the range of non-dimensional parameters in the experimental collection data is mentioned. In most of the models, such as the Kheyrabad, Jareh, Azad, Doosti, Gotvand Olya, Siazakh, Seymareh, Karun 3, Raeesali Delvari, Mamloo, Nyan, Mansion, Chamyshir, Karkheh, Karun 4 and Ostoor dams, the spillway is not a part of the dam body, and the flow passes through the guide walls (Figure 3). However, eight gates were designed in the dam body of Salman Farsi according to Figure 3.

The number of radial gates on the crest varies from 2 to 8 in the models studied. In most physical models, the downstream weir face forms follow from the form of $y/H_D=-K\ (x/H_D)^n$. However, in the physical model of the Ssiazakh dam, the weir face is completely different from the standard Ogee spillway. Accordingly, the differences in *K* and *n* and the form of downstream weir face in the set of studied models can be used to examine the applicability of the previous proposed methods for estimating the discharge of gated spillways.

Also in the physical models of Salman Farsi and Siazakh dams, arched spillway could affect errors in estimating the discharge of gated spillways by the previous methods.

In most laboratory experiments, all designed gates have the same openings. However, in the findings of the physical models of the Ostoor and Salman Farsi flood discharge systems, a number of experiments relate to the operation of one or more gates from a set of the gates.

In the data collection, the relative position of the gate seat is located at $0.1\leq X_s/H_D\leq0.4$, which provides an appropriate examination of the effect of the gate seat on the discharge estimation.

Another advantage of the data is the existence of 31 data series related to the transitional flow range ($y_L/H_1>0.77$), which is mainly related to the physical model of the Mamlou flood discharge system.

Table 1- Range of effective non-dimensional parameters in the present experimental observations.

Non-Dimensional Parameters	K	n	m	R/H_d	Y_T/H_d	P/H_d	X_s/H_d	b_p/b
Range	0.24-0.70	1.00-1.85	0-1.03	0.68-1.97	0.25-0.66	0.15-2.25	0.10-0.40	0.20-0.57
Non-Dimensional Parameters	N	We	Re	β°	H_2/H_D	w/H_D	C_{dexp}	Q^*_{exp}
Range	2-8	$(2.9\text{-}349)\times10^5$	$(4\text{-}65)\times10^6$	52.2-98.2	0.01-1.27	0.07-0.79	0.39-0.92	0.57-3.99

Figure 3- Images from hydraulic models of flood discharge systems in the present study

3. Results and Discussions

Dimensional Analysis

From Table (1), the discharge of the spillways with radial gate is a function of different parameters which can be defined as follows:

$$F\left(b_p, b, R, \mathrm{Y}_T, \mathrm{X}_T, X_S, P, m, \begin{Bmatrix} H_1 \\ H_2 \\ H \end{Bmatrix}, \mathrm{r}, H_D, \mathrm{y}_{L(i)}, k, n, \nu, \sigma, \mathrm{g}, \rho, \mathrm{Q}_i\right) = 0 \tag{4}$$

On the other hand, it can be shown:

$$x_{c(i)} = f_2\left(k, n, y_{L(i)}, X_T, R, Y_T\right) \tag{5}$$

$$\beta_i = f_3\left(k, n, x_{c(i)}, y_{L(i)}, Y_T, R\right) \tag{6}$$

As a result of Equations (5) and (6), it can be shown that,

$$\beta_i = F_1\left(k, \mathrm{n}, \mathrm{y}_{L(i)}, \mathrm{X}_T, R, Y_T\right) \tag{7}$$

The functional relation (4) will be obtained as follows:

$$F\left(b_p, b, X_S, P, m, \mathrm{r}, H_2, H_D, y_{Li}, \nu, \sigma, \mathrm{g}, \rho, \beta_i, \mathrm{Q}_i\right) = 0 \tag{8}$$

in which β_i and *m* are non-dimensional parameters. From Equation (8), the total number of dimensional variables is n=13 and from all three geometric, kinematic, and dynamic parameters there is at least one parameter in the set of parameters. As a result, 10 non-dimensional parameters need to be as a follows:

$$\pi_1 = \frac{X_S}{H_D}, \pi_2 = \frac{P}{H_D}, \pi_3 = R_e, \pi_4 = We, \pi_5 = \frac{b}{H_D}, \pi_6 = \frac{b_p}{H_D}, \pi_7 = \frac{r}{H_D}, \pi_8 = \frac{H_2}{H_D}, \\ \pi_9 = \frac{y_{Li}}{H_D}, \pi_{10} = \frac{Q_i}{\sqrt{gH_D{}^5}} \tag{9}$$

Due to the combination of non-dimensional parameters, and ignoring from Reynolds and Webber Numbers due to their significant amounts within the scope of the present research (Table 2), the following dimensional relationship is achievable:

$$Q_i^* = \frac{Q_i}{b\sqrt{gw_i{}^3}} = f\left(\beta_i, m, \frac{X_S}{H_D}, \frac{P}{H_D}, \frac{b_p}{b}, \frac{b}{H_D}, \frac{r}{H_D}, \frac{H_2}{y_{L(i)}}, \frac{y_{L(i)}}{H_D}\right) \tag{10}$$

Derivation of Geometric Relations for Explicit Estimation of *β* and *w*:

Discharge estimation of the spillway with radial gate using USACE (1977)'s method needs to calculate *β* and *w*. As mentioned above, determining these parameters in USACE (1977)'s method requires several steps and the use of three hydraulic design charts. Also, this method is limited to the standard ogee spillways and a different shape lead to an error in the calculation *β* and *w*. Generally, gate lip and weir crest levels ($E.L._L$ and $E.L._o$, respectively) are known. As a result, the vertical opening of the gate will be known ($y_L=E.L._L-E.L._o$). Taking into account the general form ($y/H_D=-K(x/H_D)^n$) for the downstream face of a gated spillway and knowing y_L,H_D, Y_T, R, K, n, reservoir level ($E.L._R$) and gate seat level ($E.L._S$), it can be shown that,

$$\frac{x_T}{H_D} = \frac{x_S}{H_D} - \sqrt{\left(\frac{R}{H_D}\right)^2 - \left(\frac{Y_T}{H_D} - \frac{y_S}{H_D}\right)^2} \tag{11}$$

$$\frac{x_L}{H_D} = \frac{x_T}{H_D} - \sqrt{\left(\frac{R}{H_D}\right)^2 - \left(\frac{Y_T}{H_D} - \frac{y_L}{H_D}\right)^2} \tag{12}$$

As shown in Figure (2), point C has the smallest distance from the downstream edge of the gate. This point is over the weir. Consequently,

$$\frac{y_c}{H_D} = -k\left(\frac{x_c}{H_D}\right)^n \tag{13}$$

On the other hand, the passage line from points L and C is perpendicular to the weir face at C and therefore it can be shown:

$$\frac{\frac{y_L}{H_D} + k\left(\frac{x_c}{H_D}\right)^n}{\frac{x_L}{H_D} - \frac{x_c}{H_D}} \times kn\left(\frac{x_c}{H_D}\right)^{n-1} = 1 \tag{14}$$

Thus, by knowing x_L/H_D and x_C/H_D from Equations (12) and (14), y_C/H_D is determined from Equation (13). Also, the distance of point L from the MC line is equal to the gate opening (*w*) (Figure 2):

$$\frac{w}{H_D}=\frac{\left|\frac{y_L}{H_D}+kn\left(\frac{x_c}{H_D}\right)^{n-1}\frac{x_L}{H_D}+k(1-n)\left(\frac{x_c}{H_D}\right)^{n}\right|}{\sqrt{1+\left[kn\left(\frac{x_c}{H_D}\right)^{n-1}\right]^2}} \tag{15}$$

The angle of tangent tangency on the weir at point C, along the horizon, is:

$$\theta=\tan^{-1}\left|-kn\left(\frac{x_c}{H_D}\right)^{n-1}\right| \tag{16}$$

Also, the gate lip angle can be found from the following equation:

$$\alpha=\sin^{-1}\left[\frac{\frac{Y_T}{H_D}-\frac{y_L}{H_D}}{\frac{R}{H_D}}\right] \tag{17}$$

Finally, the angle *β* can be obtained from the following equation:

$$\beta=\frac{\pi}{2}-\theta-\alpha \tag{18}$$

Table (3), shows some examples for calculating β and w which presented by USACE (1977)'s method from the Hydraulic Design Chart 311-2. These examples were defined for a standard ogee spillway with radial gate ($y/H_D=-0.5(x/H_D)^{1.85}$, $X_S=0.1^x H_D$,$R=0.831^x H_D$, $X_T=0.907^x H_D$, $Y_T=0.324^x H_D$, $H_D=37$ ft). Tale (3) also compares the results of USACE (1977)'s method with the new method in the present study for calculating β. It can be seen that the present study accurately estimate β and w without the need for a set of graphs as mentioned in USACE (1977)'s method.

Table (3)- comparison between USACE (1977) and present study for calculating β and w [Hydraulic Design Chart 311-2]

y_L (ft)	x_L (ft)	x_c (ft)	y_c (ft)	w (ft)	w/HD	α°	ǀmǀ	θ°	β° Present Study	β° USACE (1977)
3.700	3.950	3.464	-0.231	3.936	0.106	15.638	0.124	7.043	67.319	67.200
7.400	3.156	2.461	-0.123	7.438	0.201	8.582	0.092	5.279	76.140	76.080
11.100	2.825	1.970	-0.081	11.062	0.299	1.655	0.076	4.372	83.973	83.980
14.800	2.941	1.859	-0.073	14.753	0.399	-5.247	0.073	4.162	91.085	91.200

The new proposed method also can be used for gated spillways with the different downstream weir face in comparison with the standard ogee spillways. For example, the downstream weir face at the gated spillway at Apalachia dam follows from the different shape ($y=-x^3/27000+x^2/68+x/15$). Figure (3) compares the variation of β, x_c/H_D, x_L/H_d, y_c/H_d, w/H_d, α, ǀθǀ,ǀmǀ with y_L/H_d using the new proposed method and for three gated spillways with the different downstream faces (Ogee standard spillway, Kheirabad dam in Iran and Apalachia dam in USA).

For an ogee standard spillway with radial gate ($y/H_D=-0.5(x/H_D)^{1.85}$, $X_S=0.1^x H_D$,$R=0.831^x H_D$, $X_T=0.907^x H_D$, $Y_T=0.324^x H_D$), the following equations can be used for explicit estimation of β and w:

$$\beta=\begin{cases}\dfrac{57.2+207.94\left(\dfrac{y_L}{H_D}\right)}{1+1.58\left(\dfrac{y_L}{H_D}\right)-0.55\left(\dfrac{y_L}{H_D}\right)^2}, & \dfrac{y_L}{H_D}\geq 0\\ 57.2+109.683\left(\dfrac{y_L}{H_D}\right), & \dfrac{y_L}{H_D}\leq 0\end{cases} \tag{19}$$

$$\frac{w}{H_D}=\begin{cases}\dfrac{0.013+0.933\left(\dfrac{y_L}{H_D}\right)}{1-0.1\left(\dfrac{y_L}{H_D}\right)+0.013\left(\dfrac{y_L}{H_D}\right)^2}, & \dfrac{y_L}{H_D}\geq 0\\ 0.013+0.908\left(\dfrac{y_L}{H_D}\right), & \dfrac{y_L}{H_D}\leq 0\end{cases} \tag{20}$$

Evaluation of Different Methods for the Discharge Estimation of Spillways with Radial Gate:

Based on the 912 series of experimental data collected in the present study, it is possible to evaluate and compare the capability of different methods for the discharge estimation of gated spillways as a part of the flood discharge system in large dams. Table (4) shows the specification of gated spillways studied in this research. Also, Table (4) and Figure (5) present the values of Mean Absolute Relative Error (MARE) for discharge estimation of gated spillways by the different methods.

Based on all experimental data, the Mean Absolute Relative Errors (MARE) for discharge estimation from USACE (1977), USBR (1973) and Sinniger and Hager (1989) are 6.9%, 9.1%, and 5.1%, respectively. The range of variation in the average values of the relative errors in discharge estimation of gated spillways using above mentioned equations is (2.48%-10.69%), (2.01%-22.28%) and (1.86%-11.86%), respectively (Table 4). Consequently, Sinniger and Hager (1989) has improved the accuracy of the discharge estimation of spillways with radial gate, significantly. The limited range of variation in the Sinniger and Hager (1989) method indicates that the dominant parameters (*β* and *w*) have been considered in this method. Also, the discharge estimation of gated spillways using the based form according Equation (2) is more accurately compared to Equation (1).

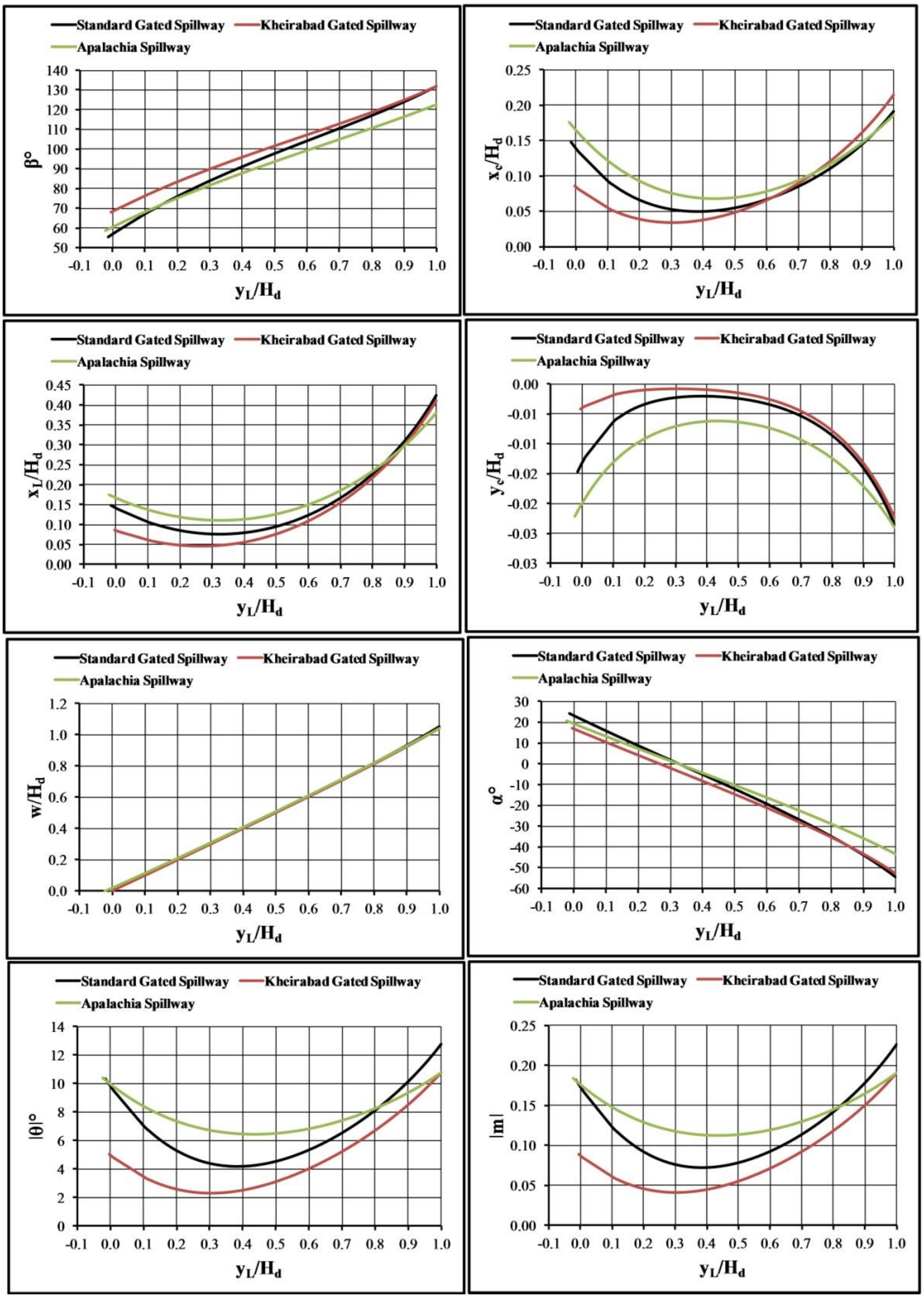

Figure (3)- Variation of β, x_c/H_D, x_L/H_d, y_c/H_d, w/H_d, α, |θ|,|m| with y_L/H_d using the new proposed method and for three gated spillways with the different downstream face

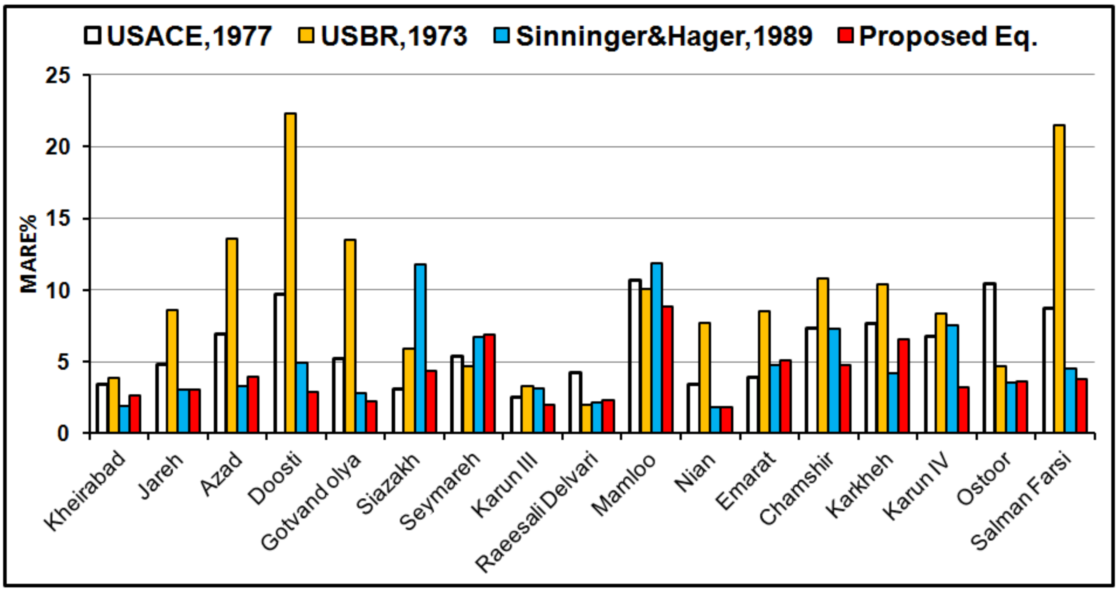

Figure (5)- Evaluation of different methods for the discharge estimation of spillways with radial gate

In the present study, especially for experimental observation of the hydraulic model of Mamloo dam, a part of experimental data related to the operation of gated spillway under transition zone between orifice and non-orifice flow conditions. Figure (6) shows the discharge values from USACE (1977)'s method and the corresponding values from experimental observations on the hydraulic model of Mamloo dam. In the present study, based of the proposed criterion by Hager and Bermen (1988), the range of $0.77< y_L/H_1<1$ is considered as a transition zone. It can be seen that using USACE (1977)'s method gives the mean absolute relative error about 25.7% and 11.6% for the discharge estimation under non-orifice and transition flow conditions, respectively.

For passing the low discharge from the gated spillways, it is necessary to adjust the gates with a small opening. In these conditions, the gate may be operated under transition zone. One solution to prevent the operation of the gate under transition zone is setting one or more gates with the greater openings and closing the others. However, this solution is not very desirable due to the effects of supercritical flow extracting from the one gate over the downstream of chute spillway.

Figure (7) compares the capability of different methods for the discharge estimation of the spillway with radial gate using collected data under the gated and transition flow conditions. The MARE% for the orifice flow condition from USACE (1977), USBR (1973) and Sinniger and Hager (1989) are 6.7%, 9.2% and 4.5%, respectively. Consequently, Equation (2) is more applicable for discharge estimation under orifice flow conditions. It can be shown that Equation (1) changes to Equation (2) for the ratio of w/H_1 lower that a certain value.

The MARE% for the transition flow condition from USACE (1977), USBR (1973) and Sinniger and Hager (1989) are 13.9%, 5.4% and 22.2%, respectively. Consequently, the accuracy of USACE (1977) and Sinniger and Hager (1989) methods considerably decrease under transition flow condition. On the other hand, due to the general form of Equation (1) USBR (1973)'s method, this method is much more efficient than the two other methods for the discharge estimation in the transition zone. Consequently, it is necessary to provide some methods for accurate flow estimation of the gated spillways continuously from non-orifice to orifice flow conditions.

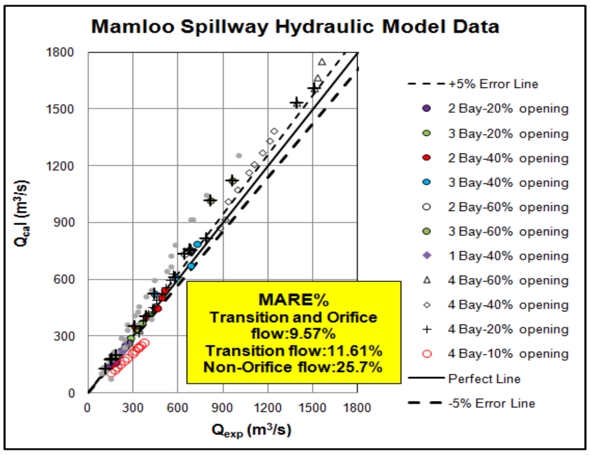

Figure (6)- Evaluation of USACE (1977)'s method for the discharge estimation under transition zone (Mamloo spillway)

Figure (8) shows the capability of USACE (1977)'s method for the discharge calculating based on the data from hydraulic models of Doosti, Karkheh and Salman Farsi spillways. It was obviously that the values of MARE for the three above models are greater than the correspond value which computed based on all experimental data. In all three models, all gates have the same opening and have been operated in gated flow condition. on the other hand, the downstream face of spillway follows from the standard ogee shape. It seems that the main reason for the increase of the error of estimating the discharge in these three models is increasing the number of gates over the spillway. It can be seen from Figure 8 In most cases, the actual flow rate is greater than the calculated values using the USACE (1977)'s method. In the presence of multi gates over the spillway, flow pattern behind of each gate affected by adjacent gates. In these cases, the discharge of gated spillways is different from the provided value based on equations which have been developed for operation of one or limited gate. As a result, it is necessary to take more precaution regarding the application of USACE (1977)'s method in terms of the designation a lot of the gates over the spillway.

From Table (4) and Figure 9(a), It can be seen that the Mean Absolute Relative Error for discharge estimation using Sinniger and Hager (1989) method (as the best method which mentioned above) considerably increases to about 11.68% based on the data from the Siazakh hydraulic model. The reason is that the proposed equation by Sinniger and Hager (1989) for calculation β and w is only valid for an ogee standard spillway. While, the crest of Siazakh spillway is a part of an arch and the downstream face of the weir is different from the ogee shape (Figure 9b, c). In this case, the proposed relation by Sinniger and Hager (1989) has an error in the determination of β and w. However, the proposed method in the present study can be used to determine the above parameters and for all downstream faces of gated spillways in general.

Figures (10) and (11) shows increasing the error of discharge estimation affected by operating one gate from the several gates. It can be seen from Figure (10) that the MARE% increases to 10.3%, 9.9% and 11.1%, respectively, when the left gate, central gate and right gate operated uniquely in the Ostoor spillway. Also, the data from the hydraulic model of Salman Farsi spillway shows that the MARE values for only operating the central gates, the pair of right gates and the pair of left gates are about 9.3%, 10.6% and 9.8%, respectively (Figure 11). It is interesting that the MARE for discharge estimation by USACE (1977)'s method considerably decreases to 6.4% when all gates are operated with the same openings. This is due to the effect of the fatigue flow lines behind of the closed gates on the pattern of open-gate flow lines. On the other hands, USACE (1977)'s method was developed based on a limited observation in which at least three gates have been operated simultaneously on the same gate openings. Consequently, it is expected that for these conditions, the actual values of the discharge will be reduced to the corresponding values from the USACE (1977)'s method. This result is in agreement with Figures (10) and (11).

There are some other uncertainties in the discharge estimation of gated spillways as a flood discharge system in large dams. For example, the presence of guide walls, the distance of the gate from the center, affected the discharge of each gate. It seems that the discharge increases by increasing the distance of the gate from the center of guide wall. This requires more experimental observations.

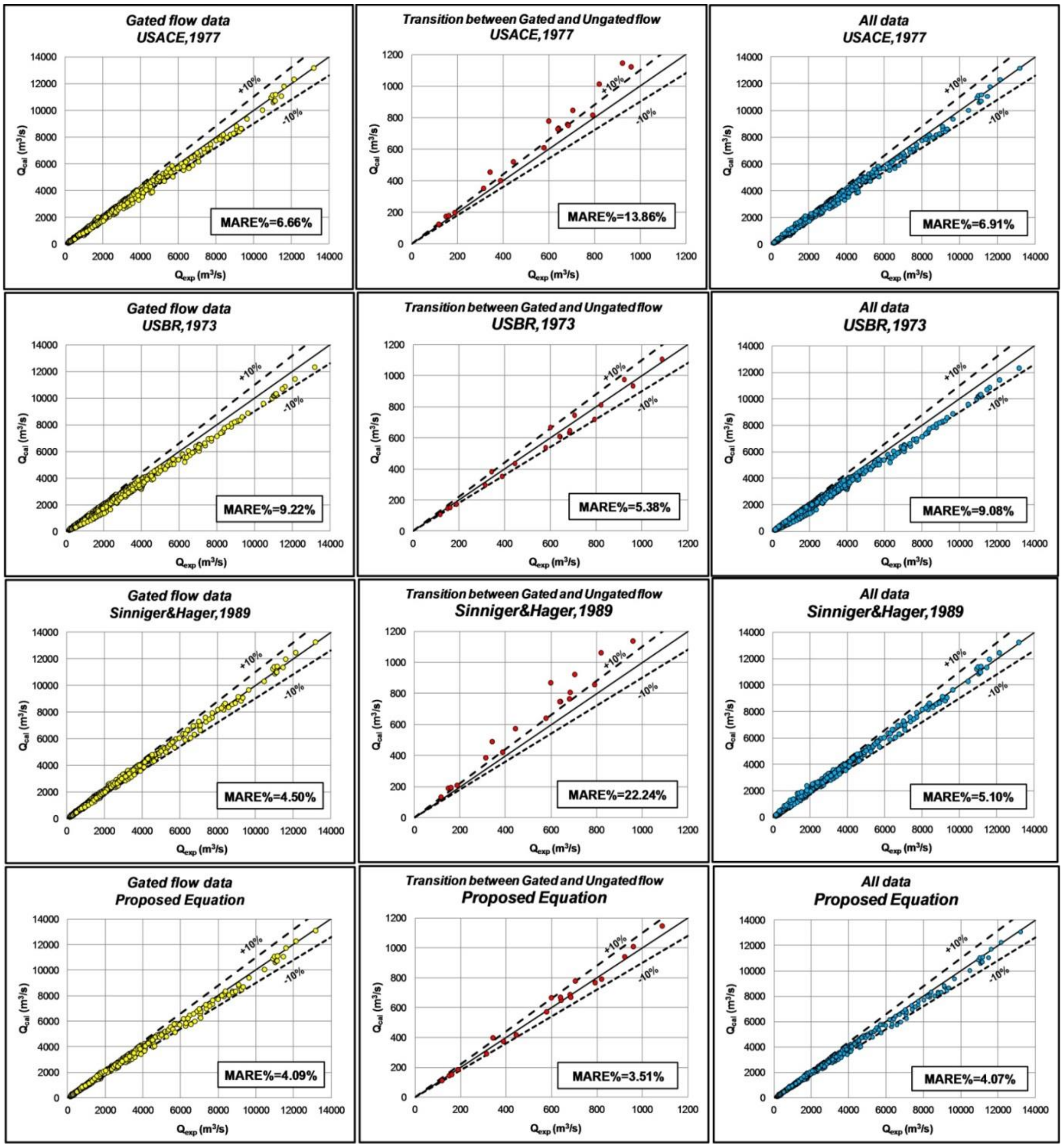

Figure (7)- Evaluation of different methods for the discharge estimation of gated spillways using Gated and Transition flow data

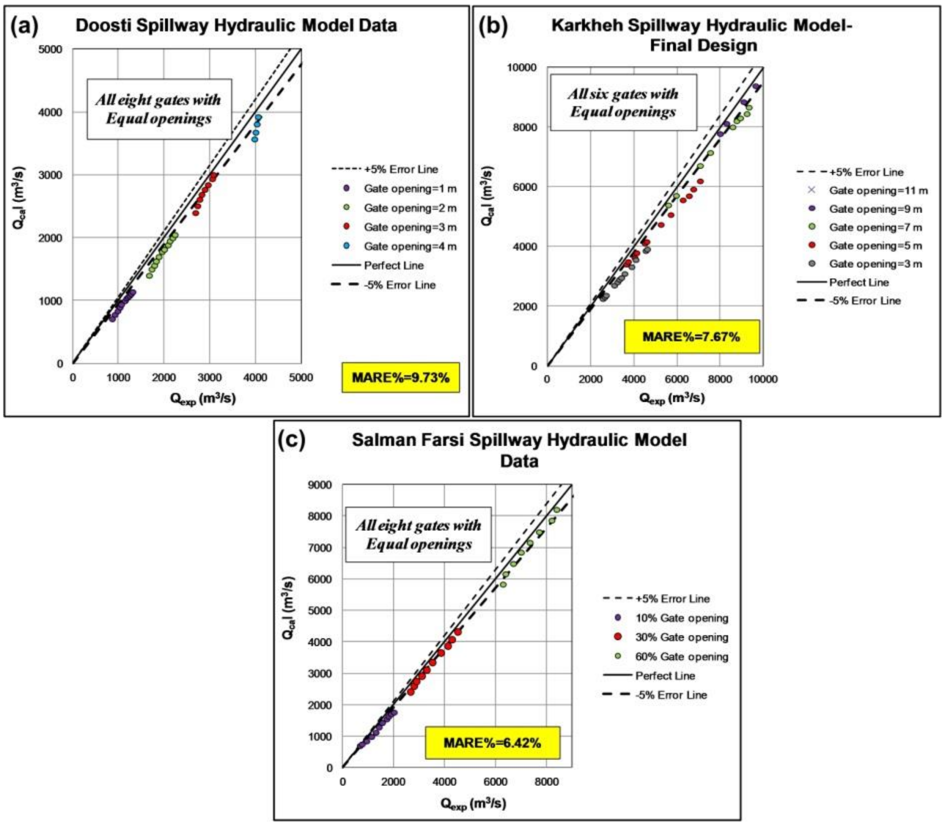

Figure (8)- Effect of downstream weir face on the discharge estimation of gated spillway using USACE (1977)'s method

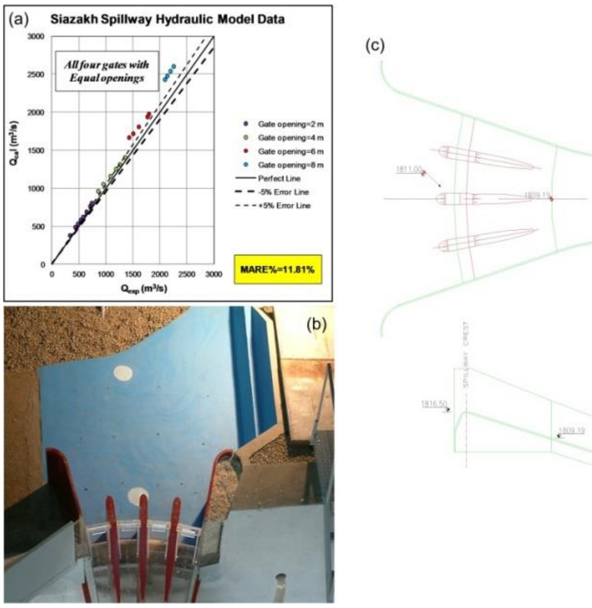

Figure (9)- Siazakh Hydraulic Model (a) Discharge values from Sinniger and Hager (1989) against observation data (b), (c) Image and asbuilt map

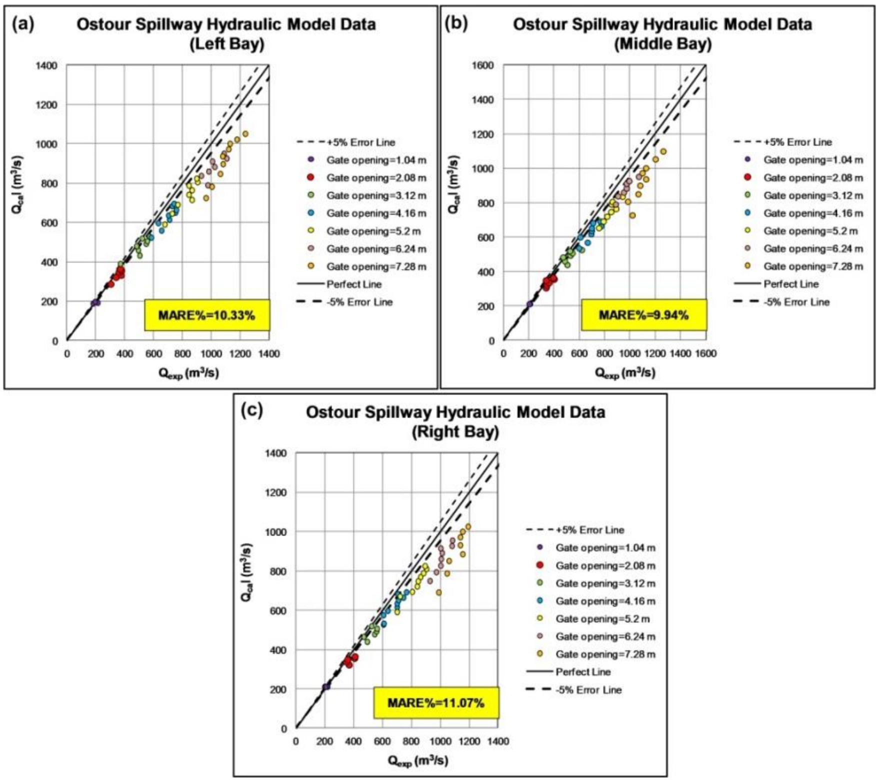

Figure (10)- Effect of the operation of one gate from several gates on the rising of the error in discharge estimation (Ostoor Spillway)

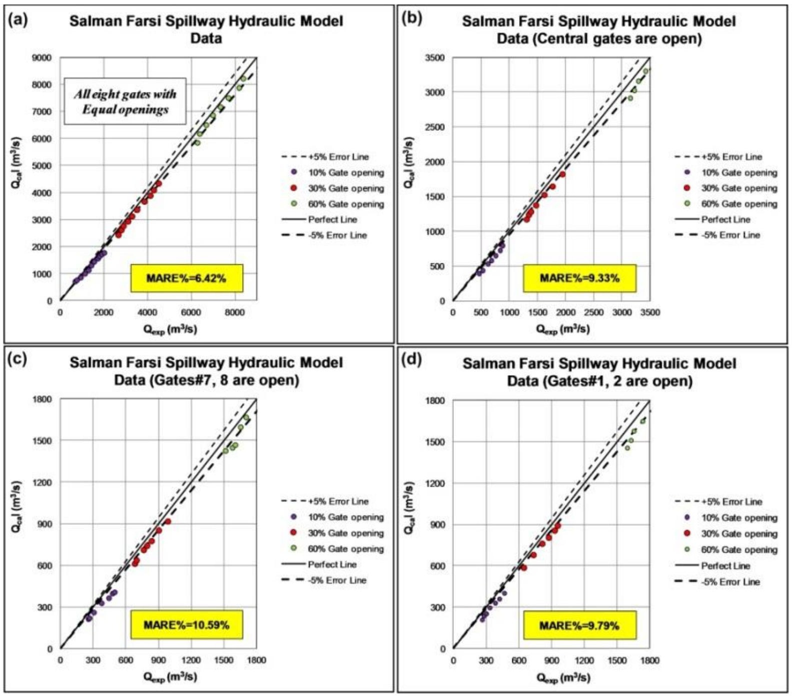

Figure (11)- Effect of the operation of one gate from several gates on the rising of the error in discharge estimation (Salman Farsi Spillway)

Development a New Equation for Discharge Estimation of Spillways with Radial Gate:

Figure (12) shows the variation of C_d with β from the USACE (1977)'s method using the data series from 17 hydraulic models. It can be seen that the discharge coefficient depends on other parameters in addition to β and X_S/H_D. Equation (10) presents non-dimensional parameters which affected the discharge of gated spillways as a part of the flood discharge system in large dams. Based on Table (2), the effects of Reynolds and Webber Numbers have been ignored.

In large dams, the discharge of gated spillways is influenced by the guide walls. Accordingly, the discharge changes with the radial distance. For this reason, the ratio of r/H_D is considered in Equation (10). Unfortunately, most of the experiments in this study were performed when the all gates operated with the same opening. Consequently, the data series at the present study is not sufficient to evaluate the effect of r/H_D. Accordingly, the ratio of r/H_D is ignored in Equation (10).

To find out the importance of various independent variables in predicting $Q^*=Q/(N.b.\sqrt{(g.w^3)})$ (Q is the total discharge), feature selection and variable screening have been carried out using *F*-Test. A *F*-Test is any statistical test in which the test statistic has an *F*- distribution under the null hypothesis (*F*= explained variance/unexplained variance).

The least *F*-value parameter is dropped because this parameter is considered as not affecting the whole value of the equation. As shown in Figure (13), H_2/y_L, β and y_L/H_D have the greatest effect on the Q^*. Other parameters show the least importance and are, therefore, dropped while deriving the relationship for Q^*.

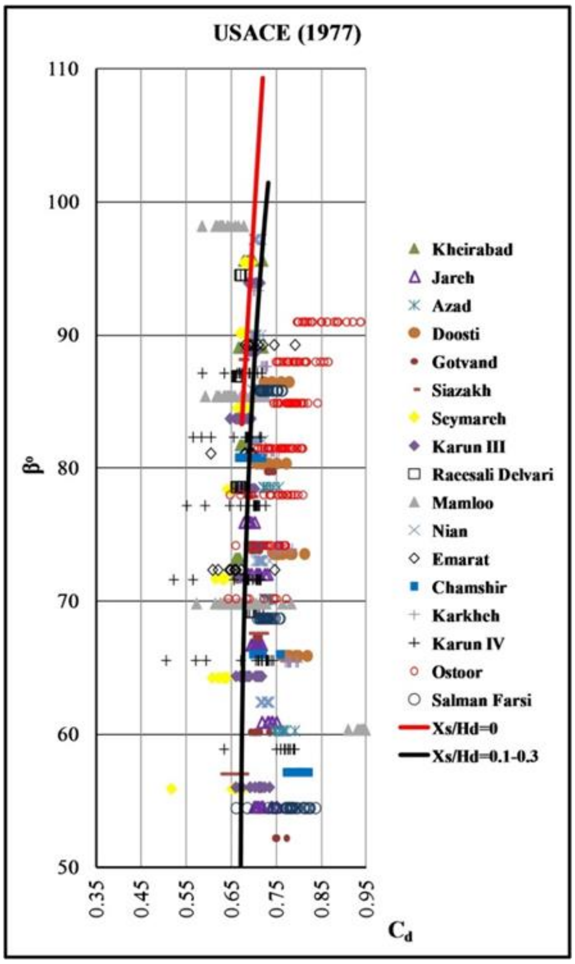

Figure (12)- variation of C_d with β and X_S/H_D based on hydraulic model data

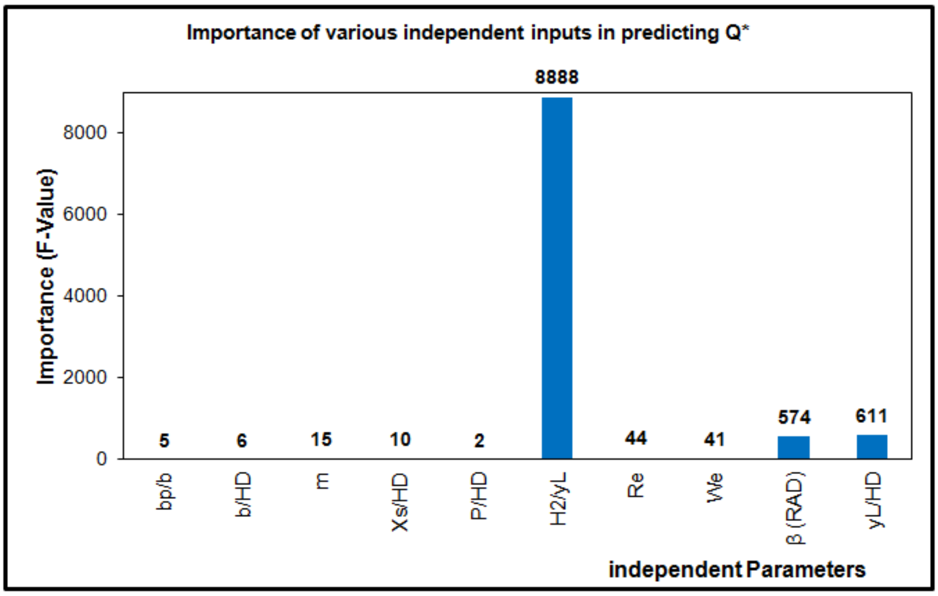

Figure (13)- Importance of various independent inputs in predicting *Q**

Finally, the following equation was proposed for estimating the discharge of gated spillways in relation with the most effective parameters:

$$Q^* = a\left(\frac{H_2}{y_L}\right)^{[b+c\times\beta]} + d\left(\frac{y_L}{H_D}\right)^{e} + f \qquad (21)$$

where *a*, *b*, *c*, *d*, *e* and *f* are constant parameters which can be found from the experimental data. In Equation (21), the angle of β is in radians. Using 912 data series from the 17 hydraulic models, the values of above mentioned parameters are 0.752, 0.633, -0.060, 0.323, 0.162 and 0.174, respectively.

Table (4) presents a comparison for the accuracy of Equation (21) with other methods in discharge estimation of gated spillways based on the data from 17 hydraulic models. Also, Figure (7) shows the capability of Equation (21) for discharge estimation under the different flow conditions. The following results were obtained:

1- Based on all experimental data, the MARE% from the Equation (21) was obtained about 4.07%. Accordingly, the new proposed method has increased the precision of discharge estimation in comparison with the previous equations.
2- Under orifice flow (Gate flow) condition, the MARE% from the Equation (21) was obtained 4.9% which is more accurate than the other methods.
3- Under transition zone, Equation (21) calculates the discharge of gated spillways with MARE% about 3.5%. Interestingly, Equation (21) is more accurate for discharge estimation under transition flow condition. As a result, the new proposed method, unlike other previous methods, can be used for accurate discharge estimation of gated spillways with radial gate under orifice and transition flow conditions.
4- Based on data series of the hydraulic models of Doosti and Salman Farsi spillways, the MARE%, considerably decreases to 2.9 and 3.8% respectively. Consequently, Equation (21) can be used for accurate discharge estimation in the presence a large number of radial gates over the spillways.
5- Based on data series of the hydraulic models of Siazakh spillway, the MARE% considerably decreases to 4.38. Consequently, Equation (21) can be used for accurate discharge estimation of gated spillways with non-ogee shape of the downstream face.
6- The data from the hydraulic model of Ostoor dam have been collected where only one gate was operated from the several gates. In this condition, the MARE% from Equation (21) considerably decreases to about 3.58%. However, the assurance about the capability of new proposed equation in this case, requires more experimental observations under operation of one gate from the several gates.

The experimental data in this research were collected when the all gates have the same opening. As a result, it is suggested the development of new equations for operating multi gates with the different opening. It is also necessary to investigate the effect of oblique approach flow over the discharge passing of gated spillway.

4. CONCLUSIONS

This paper presents to evaluate the capability of different methods for discharge estimation of spillways with radial gate as a part of the flood discharge system in large dams. For this, the data from 17 hydraulic models of the Iranian large reservoir dams was used. Based on the Pi-Buckingham theory, effective non-dimensional parameters were determined. Based on the F-Test and using of a set of experimental data, the effect of different parameters on the discharge estimation was compared. Also, a new relationship was developed to estimate the discharge of gated spillways in relation with the most important parameters and its constants was calibrated based on experimental data. Based on geometric analyses, some relations were presented for simple estimation of the parameters β and w. This method can be used for the different shapes of downstream weir faces. Based on experimental data, Equation (21) can be used for accurate discharge estimation of spillways with radial gate under orifice and transition flow conditions. However, it is necessary to develop new relationships to estimate the discharge of spillway with multi gates when the gates have the different openings. Also, it is recommended to study the effect of oblique approach flow over the discharge of gated spillway.

5. ACKNOWLEDGMENT

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6. REFERENCES

1. U.S. Bureau of Reclamation (USBR). (1973). Design of small dams, U.S. Government Printing Office, Washington, D.C.
2. U. S. Army Engineer Waterways Experiment Station, CE, Discharge Rating Curves for Vertical Lift Gates on Spillway Crests, by R. H. Multer. Miscellaneous Paper No. 2-606, Vicksburg, Miss., October 1977.
3. Sinniger R. O. and Hager W. H. (1989). Constructions Hydrauliques, Presses Polytechnique Romanades, pp 197-201.
4. Hussain, S., Hussain, A. And Ahmad, Z. (2014). Discharge characteristics of orifice spillway under oblique approach flow. Vol (39). pp. 9-18
5. Hager, W. and Bremen, R. (1988). Plan Gate on Standard Spillway. J. Hydraul. Eng., 114(11), pp. 1390 1397.