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NEW APPROACH TO DISCHARGE CALCULATION UNDER CANAL RADIAL GATES

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Abstract

Laboratory experiments to collect adequate and appropriate data were conducted on the radial gate. The collected data are analysed for the aim of simplifying the methodology of discharge calculation under such gate in practice without losing the accuracy of the results. Two new empirical equations for the coefficient of discharge have been developed for free and submerged flow to achieve this aim. The dimensional analysis and regression were employed to derive the coefficient of discharge relationships. The solution of the derived equations requires the availability of the influential hydraulic and geometric parameters. These parameters are; the upstream flow depth, the downstream water depth near the lip of the gate, the tailwater depth (in the submerged flow condition), the gate radius, the gate opening and the gate angle of the lip. Thus, design curves were introduced along with those equations for this purpose. The solutions by the proposed formulas produced -0.2% and -0.4% residuals with free and submerged flow conditions respectively. The negative sign is an indication of the overprediction tendency.

Keywords: Coefficient of discharge, Dimensional analysis, Free flow, Radial gate, Submerged flow.

1. Introduction

The accuracy of flow measurements is the overriding concern and the challenge that motivates researchers to create the easiest way to get it by different up to date measurement facilities (e.g., water level measurements by ultrasonic). A radial gate is one of the widely used facilities to control head and flow discharge in hydraulic applications. In irrigation canals, this type of gates is present in the head and check regulators due to its simplicity at operation (need smaller lifting forces than the other types) resisting the pressure forces through pivot points, produce lower flow disturbance, inexpensive, and has a specific accuracy.

Several factors affect the flow under a radial gate; some geometrical and others are based on hydraulic condition. The geometrical factors related to gate design and its opening, while the upstream and downstream heads are the hydraulic conditions having a direct influence on flow feature through the radial gate, by which, is classified as either free or submerged. However, the gate opening is the major geometric factor governing the amount of flow and the flow feature. It also has a direct responsibility on losses factors (i.e., discharge and contraction coefficients).

As reported by Clemmens et al. [1], the discharge calculation errors of the calibration method used for gate operating under free and submerged flow condition are ±5% and up to ±50% respectively. Accordingly, it is useful to create factors at dimensionless forms and testing the accuracy of their impact on the discharge. However, the reliability of these factors can be determined by closing the results with the measured values.

Several investigations follow the experimental and numerical techniques as an attempt to improve the discharge measurements from the radial gate. Clemmens et al. [1] develop a new calibration method for modular and non-modular flow based on the experimental study. The method uses energy and momentum equations on the upstream and downstream side, respectively. The difficulty of this method is to resort to using the iterative solution to solve these two equations. Shahrokhnia and Javan [2] introduced simple relationships based on dimensionless parameters to be used for discharge calculation in the radial gate operated under a free and submerged condition in open channels networks. The proposed equations have a good accuracy by the agreement between their results and the collection date from the field and laboratory.

Clemmens and Wahl [3] used the laboratory data for a radial gate to evaluate the energy and momentum procedure for calibration. In this work, the authors adopted the pressure distribution and the coefficients of the velocity and momentum distribution. This procedure showed that the momentum coefficient was related to the low and high submergence when its value is 1.08 and 1.3, respectively. Whereas, the energy equation had reliable results when it is used with a free flow at error location within ±2%, while for submerged flow the error was ±5% when the energy-momentum equation is found to be more reliable.

Bijankhan et al. [4] focused on the submerged flow under a radial gate, in this context the authors proposed development on the original dimensionless formula, which has been presented by Ferro [5] by taking the threshold value of the submergence. The authors are adopting the π-theorem and Incomplete self-similarity (ISS) conditions to deduce an appropriate stage-discharge relationship. Zahedani et al. [6] invested a set of experimental and field data in deriving empirical equations for both free and submerged flow conditions. The authors used a dimensional analysis and non-linear regression for deriving the proposed formulae.

Shayan et al. [7] presented different formulae for contraction coefficient based on the shape of a radial gate lip, by using both the energy and momentum equations. The authors recognized that, the contraction coefficient decreases as the gate lip angle and the gate opening increase. However, under submerged flow condition, this coefficient would be either decreased or increased depending on the stage of submergence. Abdelhaleem [8] used many field data collected from different regulators in the Delta irrigation district of Egypt, to calibrate multiple parallel radial gates. The author follows the dimensional analysis with adopting the incomplete self-similarity concepts to introduce a simple formula, by which, the discharge coefficient is implicitly considered to be used for estimating the flow rate at submerged conditions. Abdelhleem [9] conducted the experimental program on the radial gate with and without gate sill at submerged flow condition. The effect of different gate sill height on the contraction coefficient, discharge coefficient, submerged jump length, backwater depth, flow energy dissipation, and velocity distribution at different hydraulic parameters were analysed and graphically presented. The author shows that there is a negative influence of sill under submerged flow condition.

Menon and Mudgal [10] determine the contraction coefficient and the velocity coefficient for radial gates both for modular and nonmodular flow conditions. The experiments were conducted to improve the discharge characteristics by modifying the exit geometry of the radial gate by attaching a quarter of an elliptical lip. The results show that the velocity coefficient is higher for the submerged flow in comparison with the free flow, and the using of the lip induced to improve the coefficient of contraction values.

In this study, the aim is to provide design curves based on the dimensionless parameters, which considered governing parameters for the flow through the radial gate for both free and submerged conditions. However, the multi-regression analysis can also be used to devise the deterministic equation for the coefficient of discharge based on the results from the design curves. The new formulas of the present study have been created based on the data collected through the experimental program, which was conducted specifically for this study.

2. Experimental work

The glass side flume available in a hydraulic laboratory of the University of Technology-Iraq is used as a laboratory channel to install the model of the radial gate. The capacity of the flume ranged between 1.0 - 10.5 m^3/hr measured by the rotameter flow meter. In the present study, all available range of the flume has been invested in experimental runs. A radial sector of a radial gate 30 cm its pivot point installed at a height 30 cm above the flume bed has been used as a gate model. The two pieces of rubber have been glued to the side edge of the gate to prevent leakage from sideways and ensure that the flow is passing only under the gate. Six gate openings based on dimensions and geometry of laboratory flume are adopted ranged between 0.5 - 4 cm, for each opening the range of the flow rate, the upstream and the downstream flow depth for both free and submerged flow conditions and the tailwater depth have been conducted in order to accommodate the largest available flow conditions.

The upstream, the downstream, and the tailwater depths were measured by the point gauge at accuracy ± 0.1 mm. The tailgate was used to set the desired tailwater depth and identifying the modular limit between the free and submerged flow conditions. The location of measuring Vena-Contracta downstream the gate was taken at two–times the gate opening as recommended by Wahl and Clemmens [11] and it was subsequently adopted by Belaud et al. [12] and Maatooq [13]. It should be noted that, for each gate opening the angle, which is created between the contact line of the gate surface and the bottom surface of the flume θ, has been measured (in degree) by using the protractor. The schematic sketch of identification this angle is illustrated in Fig. 1.

For free flow conditions (modular flow) under the radial gate, the initial depth of the hydraulic jump was fixed at location equal 2- times the gate opening by using the adjustable tailgate. The submerged flow (non-modular limit) is defined to occur when adjusting the tailgate for the same discharge of the free flow to drown the Vena-Contracta (the location of the initial depth of the hydraulic jump) to become just in contact with an edge of the gate. This situation when achieved is considered as the modular limit, i.e., the transition state from free flow to submerged flow.

Based on studies by Maatooq [13] and Sunic [14], this procedure has been adopted, similar to what was done by previous researchers when working on the sluice gate. It is worth to note that the measurements were repeated to accommodate the change in the tailwater and headwater for submerged flow conditions and distinguished in the datasheet. A schematic definition of geometric the radial gate and the hydraulic parameters for free flow and submerged flow conditions are illustrated in Fig. 2. This figure is intended to explain the hydraulic differences that arise according to the flow state involved. The experimental data are described in Table 1 for both free and submerged flow conditions.

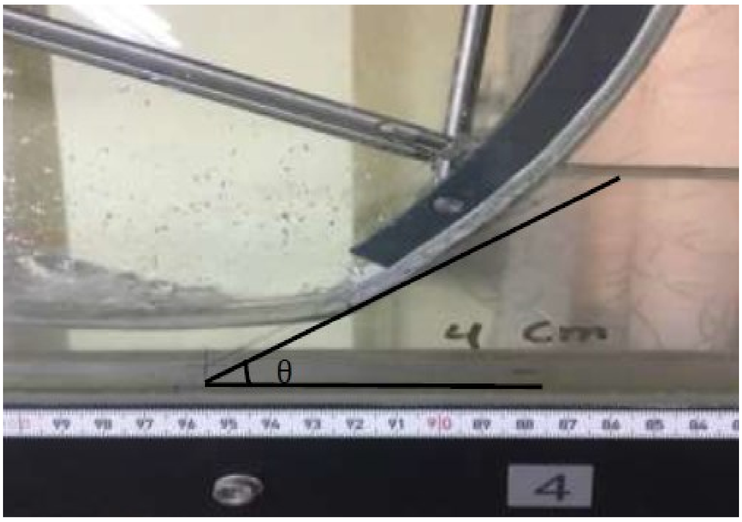

Fig. 1. Method of measuring the angle between lip and bed of flume.

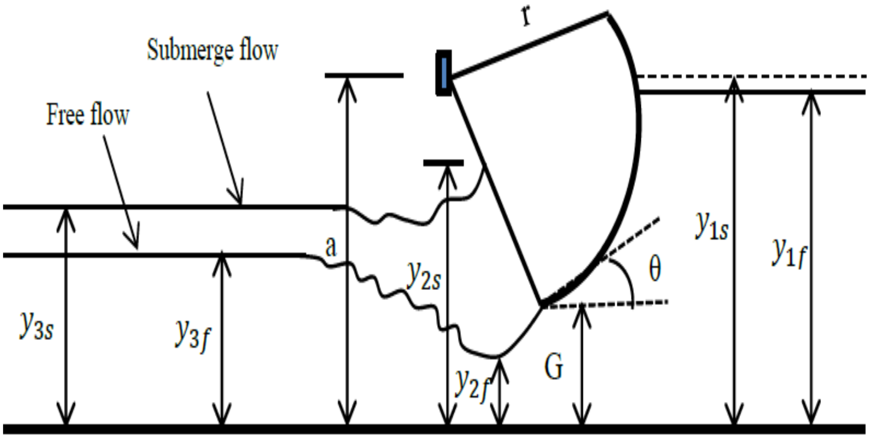

Fig. 2. Schematic definition of geometric and hydraulic characteristics of radial gate.

Table 1. Test model Specifications and test conditions.

No. of models	G^*	q m^3/s.m	Submerged flow*		Free flow*			a^*	r^*	°θ
			y_{1f}	y_{2f}	y_{1S}	y_{2S}	y_3			
6	0.5-4	0.00323-0.02907	3.5-18.6	0.43-3	4.2-22.3	1.2-5.5	2.8-11.6	40-53	30	30

*dimensions in (cm)

3. Dimensional Analysis

To be inconsistent with the context of previous studies and in order that the results of this study are close to the practical application after the process of analysis, the dimensionless functional relationship has been adopted. The discharge is a dependent variable definitely influenced by different hydraulic and geometric parameters. With the help of the π-theorem, the general dimensionless functional relationship takes the following form

$$\frac{q}{\sqrt{gG^3}} = f\left(\frac{y_1}{G}, \frac{y_2}{G}, \frac{y_3}{G}, \frac{r}{G}, \frac{a}{G}, \theta, R_e\right) \tag{1}$$

At which, q is the unit discharge and Re is Reynold's number, where it related to the characteristics of the flow under the gate opening. The other parameters are illustrated in Fig. 2.

As well-known, the conventional methods for discharge calculation under gates for both free and submerged flow conditions are derived from energy and momentum principles. For the rail water flow under gates, the energy loss is determining within the coefficient, of which, taking into consideration the effects of the geometric and hydraulic determinants of the structure at a specified operation. Often, the coefficient of discharge is adopted usually to accommodate these determinants.

For rectangular cross-section and when the tailwater does not affect the sequent depth of the hydraulic jump, which is created downstream the gate, the discharge equation takes the form.

$$q = C_d G\sqrt{2gy_1} \tag{2}$$

where C_d is the discharge coefficient. As stated by Abdelhaleem [8] the discharge coefficient is a function of the contraction coefficient, which in turn varies with the gate opening, shape and geometry of the gate lip, upstream water depth and the gate type. All of these parameters are characterized as the dimensionless form at Eq. (1). In practice, it is highly difficult to determine the precise value for a discharge coefficient.

When the flow is drawn towards the lip of the gate, it means the tailwater has a predominant effect on the flow feature under the gate, at which, the flow denoted as "submerged". This impact is directed on the amount of discharge and the stage of the flow at upstream. At this situation Eq. (2) being included the effect of the tailwater, thus take another feature as

$$q = C_d G\sqrt{2g(y_1 - y_3)} \tag{3}$$

The discharge coefficient, in this case, will certainly be affected by the submergence ratio.

In the present study, the aim is to introduce simple and more practical relationships between the discharge coefficient and the influencing parameters for both free and submerged flow conditions. The relationships are presented in the forms of design curves and equations. It should emphasize here that, the threshold of submergence, i.e., a modular limit has solely been adopted to represent the state of submerged flow conditions.

For the free (modular) flow condition, Eq. (1) can be reformulated as:

$$C_d = f(\frac{y_1}{G}, \frac{y_2}{G}, \frac{r}{G}, \frac{a}{G}, \theta, R_e) \tag{4}$$

Usually, in open channel flow, the inertia force dominates the viscous force the effect of Reynold's number could be eliminated accordingly without leaving a significant error. On the other hand, the integration of some factors helps to focus on determining the factors that have a direct impact on the discharge coefficient, therefore Eq. (4) will be:

$$C_d = f(\frac{y_1}{r}, \frac{y_2}{G}, \theta) \tag{5}$$

The parameter y_2/G representing the contraction coefficient C_c and it implies with the angle of lip opening θ, where there is a relationship between them as proposed by Bijankhan et al. [4], Abdelhaleem [8] and Wahl and Clemmens [11]. Accordingly, in the present study, this relationship was introduced as a design curve.

For submerged (non-modular) flow condition, the same procedure as in free flow has been followed for extracting a functional relationship between the discharge coefficient and the most influential parameters, which leads to

$$C_d = f(\frac{y_2}{G}, \frac{r}{G}, \frac{y_1}{y_3}, \theta) \tag{6}$$

The difficulties of direct measurements of the y_2 in practice in case of submerged flow induce to introduce the design curve between the r/G and y_2/G, where the former is simply identified by the geometrical design of the gate and the gate opening. In this basis, it could permit to exclude the r/G from Eq. (6) to take the final form

$$C_d = f(\frac{y_2}{G}, \frac{y_1}{y_3}, \theta) \tag{7}$$

The functional relationships presented in Eqs. (6) and (7) have been used to derive new empirical equations by using the experimental data and non-linear regression analysis, which could be simply used practically to estimate the discharge coefficient for free and submerged flow situations. However, a design curve has also been presented to integrate the calculation procedure.

4. Results and Discussion

The functional relationships of Eqs. (5) and (7) have been analysed by regression analysis by using the experimental data. The following empirical equations were developed via Minitab-18 for determining the coefficient of discharge at free and submerged flow conditions respectively.

$$C_d = 0.6683 \left(\frac{y_1}{r}\right)^{0.0231} \left(\frac{y_2}{G}\right)^{0.745} \left(\frac{\theta}{90}\right)^{-0.329} \tag{8}$$

$$C_d = 1.3703 \left(\frac{y_2}{G}\right)^{0.269} \left(\frac{y_1}{y_3}\right)^{-1.115} \left(\frac{\theta}{90}\right)^{-0.284} \tag{9}$$

The determination coefficients of these formulae are, $R^2 = 0.688$ and 0.855 respectively. The comparison was conducted between the values of C_d, which is calculated from the above two empirical equations and the counterparts from Eqs. (2) and (3) for both free and submerged flow (denoted as theoretical C_d). The results of the comparison are shown in Figs. 3 and 4, from which, it could be observed the more tendency towards the overprediction. The average percentage values of residuals confirmed this observation, where their values are; -0.2% and -0.4% for free and submerged flow, respectively.

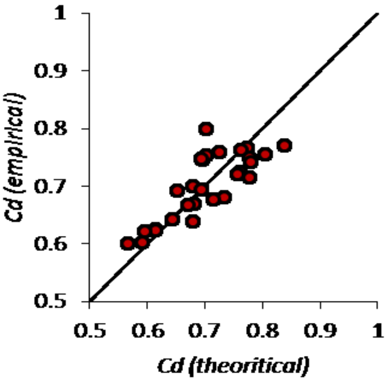

Fig. 3. Comparison of empirical with theoretical values of *Cd* for free flow.

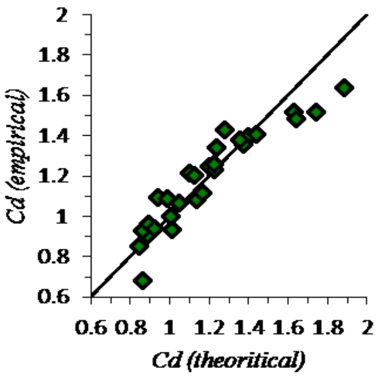

Fig. 4. Comparison of empirical with theoretical values of *Cd* for submerged flow.

The practical application of Eqs. (8) and (9) is integrated with using the design curves created based on the governed independent dimensionless parameters of these equations. These curves enable to determine the parameters are likely the site engineer facing difficulties to measure. These difficulties are arises due to multiple reasons such as; lack or loss of the instrumentation or maybe it located under the flow surface, e.g., the angle of the gate lip. The availability of the data from the experimental work has been analysed in accordance with a simplified and practical function to enable the practical engineer to overcome these difficulties through using these design curves. These curves can be invested in the site-applications without having to resort to conducting some measurements, which are difficult to achieve.

The geometric characteristics such as the radius of curvature *r* and the gate opening *G*, are often determined by the design information and operation management, respectively. Therefore, these two factors could be identified without the need for the in-situ measurements. The ratio of *r/G* can, therefore, be combined with the angle of the lip, θ to create a design curve through using the experimental data, as shown in Fig. 5. From this figure, the dimensionless term $\theta/90$ can be read and used in the application of Eqs. (8) and (9). Instead, the following relationship between $\theta/90$, and r/G at $R^2=0.978$ can be used.

$$\frac{\theta}{90} = 0.0001\left(\frac{r}{G}\right)^2 - 0.01\left(\frac{r}{G}\right) + 0.652 \tag{10}$$

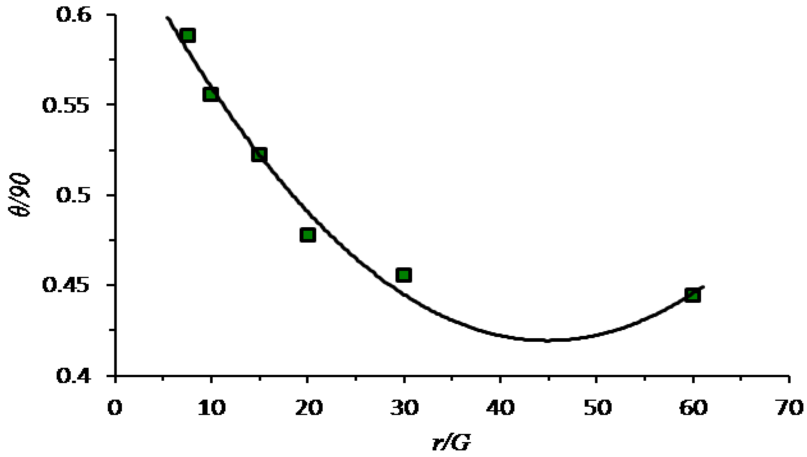

Fig. 5. Design curve for determination the gate lip angle for free and submerged flow.

Since the flow depth at upstream y_1 is usually controlled and could be measured by instrumentation, the application of Eqs. (8) and (9) needs to know the values of the flow depth just at the downstream of the gate y_2 for both free and submerged flow conditions. It is rare to get a precise measure of this depth in situ, especially with the submerged flow. Accordingly, creating a design curve through the investment of experimental data is very useful for the solution of Eqs. (8) and (9) for the on-site application.

Thus, the y_2 can be taken through the application of Figures 6 and 7 or calculated directly from the following related equations for free and submerged flow conditions respectively at $R^2 = 0.963$ and 0.984.

$$\frac{y_2}{G} = -5.295\left(\frac{\theta}{90}\right) + 4.653\left(\frac{\theta}{90}\right) - 0.1585 \tag{11}$$

$$\frac{y_2}{G} = 0.0432\left(\frac{r}{G}\right) + 1.0347 \tag{12}$$

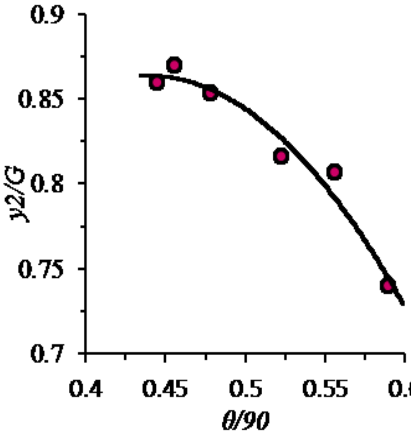

Fig. 6. Design curve for determination the downstream depth for free flow.

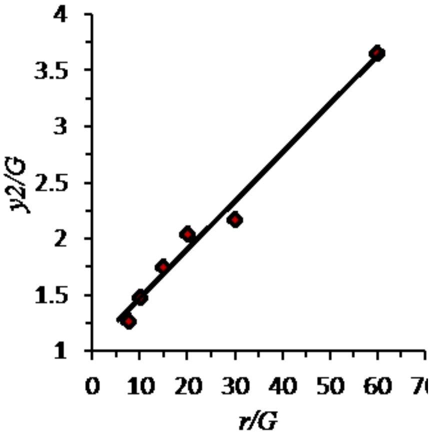

Fig. 7. Design curve for determination the downstream depth for submerged flow.

The tailwater depth is a key term in determining the state of flow when it becomes submerged. In practice, the percentage of submergence was identified by measuring y_3.

The ratio between the upstream depth y_1 and the tailwater depth y_3 can be invested to apply Eq. (9) after using Fig. 8 to determine *r/G*. It should mention that Fig. 8 was introduced here to be used just in case when the information about *r* or *G* is unavailable.

Based on this process, the potential of Fig. 5 or Eq. (10) can be used to determine the $\theta/90$ to be useful for using Eq. (9) to calculate the discharge coefficient based on the submergence ratio as encountered in practice.

It should refer to the ability to use the following equation instead of Fig. 8 in the case when direct calculation required with $R^2 = 0.939$.

$$\frac{r}{G} = 13.588\left(\frac{y_1}{y_3}\right)^2 - 12.562\left(\frac{y_1}{y_3}\right) + 3.787 \tag{13}$$

Based on the above-mentioned methodology, the empirical discharge coefficient C_d that calculated from Eqs. (8) or (9), enables using Eqs. (2) or (3) to calculate the unit discharge through the radial gate, which resulting based on specified geometric and hydraulic conditions.

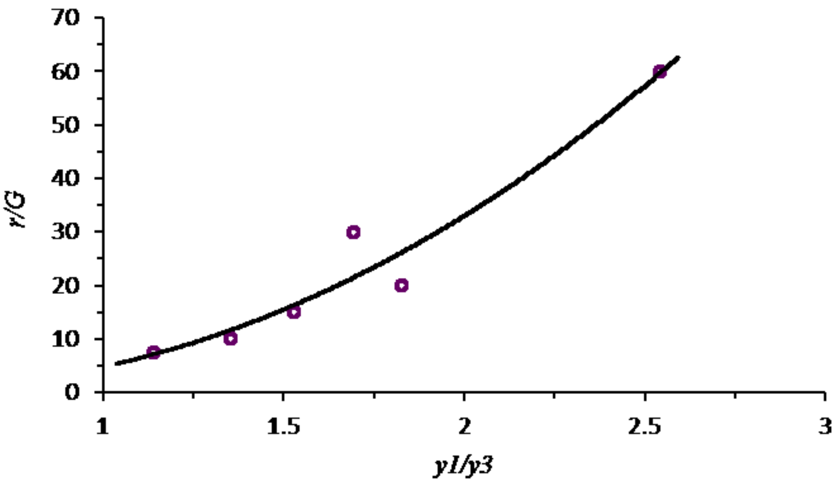

Fig. 8. Design curve for determination of the radius to gate opening ratio for submerged flow.

The usefulness of the empirical formulations, which are presented in this study could be tested through the comparison with some related equations presented in the literature. Shahrokhnia and Javan [2] and Zahedani et al. [6] have been presented new equations to estimate the discharge under a radial gate based on dimensional analysis and experimental program. It is appropriate to make a comparison with the proposed equations by those authors. This view comes because the similarity, which had mostly been followed for preparation of the experimental data and the process of analysis (for more details about the forms of equations, review the original papers of those authors).

The comparison of free flow is shown in Fig. 9, at this figure the calculation of the discharge by the equation of Shahrokhnia and Javan [2] seem in perfect agreement with the experimental discharges of the present study. The average residual was +1.5%, where the positive sign of this residual refers to underprediction. On the other hand, the good agreement is also illustrated with the equation of Zahedani et al. [6] where the calculation based of this equation is ranged between the overprediction with low ranges of discharges to the underprediction with higher stages of discharges, but as the average, the residual was -1.5%. The negative sign refers to that the calculation with the Zahedani formula generally tends to overprediction.

At submerged flow conditions, the results calculated by both equations show good agreement with the discharges that measured from the experimental work. However, over predictions seem to prevail over all ranges of discharges undertaken. Figure 10 illustrates this situation, but the equation of Zahedani et al. [6] behaves better. The average residuals with using the first and the second equations were -34% and -15% respectively, which indicate that there is the better performance when using the equation of Zahedani et al. [6] than adopting the equation of Shahrokhnia and Javan [2].

However, through reviewing the papers of Shahrokhnia and Javan [2] and Zahedani et al. [6], it was found that the choosing the equations, which proposed by the former in the application are easier than the later for both free and submerged flow conditions due to their simple forms. However, as explained above, in the case of submerged flow, the equation, which proposed by Zahedani et al. [6] comes closer to practice.

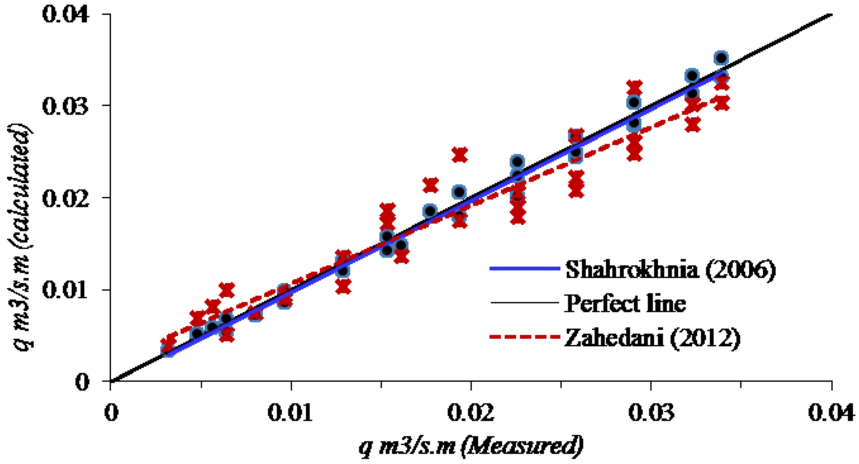

Fig. 9. Performance of some previous equations as compared with the empirical discharge at free flow condition.

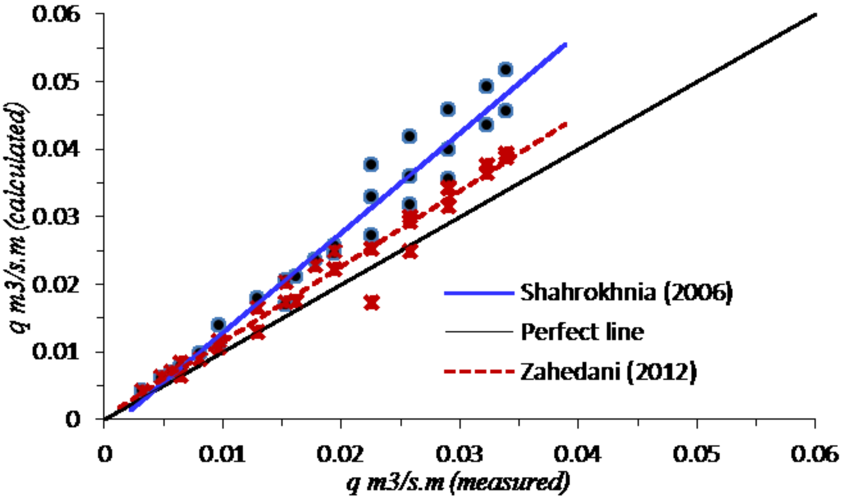

Fig. 10. Performance some previous equations as compared with the empirical discharge at submerged flow condition.

5. Conclusions

The focus of this study is to formulate the new empirical equations of the discharge coefficient for flow under the radial gate. Both the free and submerged flow conditions have been adopted at the experimental program. The intended equations aim the simplicity for the application in situ without neglecting the need to maintain the required accuracy. Sometimes, in the site, the engineer encounters difficulties to find suitable information to facilitate the necessary measurements for hydraulics and geometric characteristics that are required for calculations. On the other hand, the available formulas for discharge calculation under a radial gate are sophisticated in the application as well as being scarce.

In this study, dimensional analysis, and the regression analysis have been followed by using experimental data to create two empirical equations for the coefficient of discharge. The intended equations depend on the influential hydraulic and geometric characteristics of the radial gate. These characteristics are; the upstream flow depth, the downstream water depth near the lip of the gate, the tailwater depth (in the submerged flow condition), the gate radius, the gate opening and the gate angle of the lip. Whereas, the trunnion pin height of the gate was fixed equal to the gate radius, so its influence is excluded from the mentioned characteristics that are also considered a boundary condition of this study.

Besides the empirical equations, the study aims to present the design curves with the related equations, by which, the governed dimensionless parameters can be identified.

The solutions when conducted by the using the proposed formulas have been produced -0.2% and -0.4% residuals at free and submerged flow conditions respectively. The negative sign is an indication of the overprediction tendency.

Nomenclatures

a	Height of pivot point, m
C_c	Contraction coefficient
C_d	Discharge coefficient
G	Gate opening, m
g	Acceleration due to gravity, m/s^2
q	Discharge per unit area, m^3/s.m
Re	Reynolds number
r	Radius of curvature of gate, m
y_{1f}	Upstream depth at free flow condition, m
y_{1s}	Upstream depth at submerged flow condition, m
y_{2f}	Downstream depth at free flow condition (pre-jump depth), m
y_{3f}	Tailwater depth at free flow condition (sequent depth of free hydraulic jump), m
y_{3s}	Tailwater depth at submerged flow condition (sequent depth of submerged hydraulic jump), m
Greek Symbols	
θ	Angle of lip opening, degree

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