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Calibration of sluice gate in free and submerged flow using the simulated annealing and ant colony algorithms

Majid Heydari[1,*], Shima Abolfathi[1], Saeid Shabanlou[2]

[1]*Department of Water Science and Engineering, Faculty of Agriculture, Bu-Ali Sina Univ., Hamadan, Iran*
[2]*Department of Water Engineering, Kermanshah Branch, Islamic Azad University, Kermanshah, Iran.*

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ABSTRACT

There are found numerous methods to measure flow in open channels. The simulation of water flow in channel requires mathematic calibration of the structures in channel so that the water level and the discharge become compatible with demand. Sluice gate is one of the most important structure which can perform in free and submerged flow. In this research, there were experiments on a sluice gate mounted in lab flume of 12.5 m, 0.6 and 0.65 length, width and height, respectively, in the slope of 0.0002. Some equations of measuring the discharge from the sluice gate extracted from Energy equations and Momentum were calibrated using two metaheuristic algorithms of simulated annealing and ant colony. After the sensitivity analysis of algorithm was done, the optimal coefficients of discharge obtained for the Conventional equation of discharge in free and submerged flow was obtained 0.686, and 0.881. Also, in calibration of Energy-Momentum method for submerged flow, the optimal contraction coefficient was 0.533. finally, the methods were assessed and compared for which the statistical indexes show the favorability of results.

1. Introduction

Controlling the water volume released from dams and water level in feeding channels requires the installation of suitable structures on dams and channels so that water level and the discharge are matched with the demand. There are different methods and devices to measure the flow in open channels (Clemmens. 2002) the simulation of water flow in channel needs mathematic description and calibration of structures in channel amongst which the gates are the most important applied on free overflow or inside the water catchment and irrigation channels. (Abbaspour et al. 2001). To achieve the optimal use of these structures, and regarding the recent advances in automatic regulation of flow for spillways and conviyence networks, it is necessary to calculate the discharge coefficients in gates accurately. The operations to get the coefficients of flow equations for the structure through measurement is called calibration. Thus, gate calibration is performed to measure the flow accurately to increase the efficiency in the distribution network, and accuracy in water delivery. Accordingly, researchers have sought to find better methods to calibrate the equations which can be presented in high speed computer programs.

In irrigation networks, the gates are widely used to transmit water or control structures which can act as free or submerged in downstream. (Bijankhan et al. 2012). Sluice gate is widely used in the irrigation channels in many countries, either as checks in the canals or as flow controllers at channel turnouts (Mahmudian Shooshtari 2008). Fig. 1 shows the flow through the gate in free and submerged flow.

In this Fig. Y_1 is the upstream water depth, Y_2 is the minimum water depth after the gate in free flow state (vena contracta) [L], Y is water depth immediately after the gate in submerged flow state[L], Y_3 is water depth at the downstream gate and after turbulence[L], W is opening height[L] and Q is flow discharge [L3/T].

*Corresponding author E-mail: mheydari_ir@yahoo.com

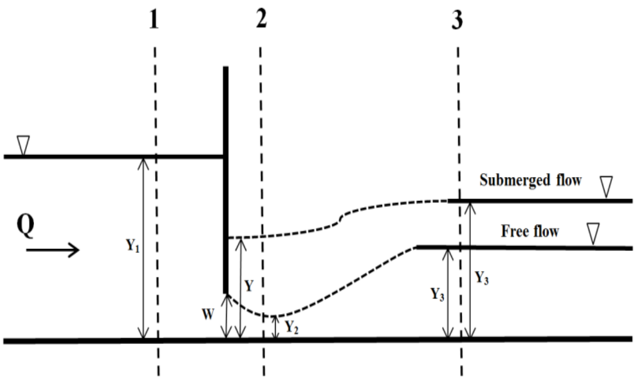

Fig. 1. The schematic figure of the flow through sluice gate in free and submerged flow.

Henry (1950) did an extensive study on sluice gates and presented graphic solutions to get the Discharge coefficient in free and submerged flow. Rajaratnam snd Subramanya (1967) applied the Energy and Momentum equation to find a rating curve equation in free and submerged flow and presented a general equation for discharge through the sluice gates in free and submerged flow.

Clemmens et al. (2003) introduced a method for calibration using Momentum equation for gate downstream and Energy equation for gate upstream, called Energy-Momentum. Lozano et al (2009) investigated some calibration methods of sluice gate using field data and found that Energy-Momentum method will have acceptable accuracy with compactness coefficient. Castro-Orgaz et al. (2010) presented a new method using Energy-Momentum principle and

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combining Energy velocity coefficients and Momentum to calibrate the submerged sluice gate and provided an acceptable accuracy for calibration method with field data. Bijankhan and Kouchakzadeh (2010) introduced a equation for transition flow from free to submerged flow derived from simultaneous solution of these two flows and found that the equations of free and submerged flows give the same results for transition flow. They used Ferro method (2001) to find the curve of flow conditions. Finally, the curve obtained showed remarkable deviation compared with that of the previous curve by Rajaratnam snd Subramanya (1967), Lin et al (2002) and Swamee (1992). Bijankhan et al (2012) introduced a dimensionless Equation for calibration which could be used in the total range of flows. Table (1) shows the equations provided by researchers to obtain Discharge coefficient.

Table 1. Some equations for Discharge coefficient of flow through sluice gate.

Equation	Flow state	Presenter
$C_d = C_c \sqrt{\dfrac{1}{1+C_c\left(\dfrac{W}{Y_1}\right)}}$	Free	(Rajaratnam 1976)
$C_d = 0.6468 - 0.1641\sqrt{\dfrac{W}{Y_1}}$	Free	(Garbrecht 1977)
$C_d = 0.62 - 0.15\sqrt{\dfrac{W}{Y_1}}$	Free	Noutsopoulos and Fanariotis (Spheerli and Hager 1999)
$C_d = 0.6\exp\left(-0.3\dfrac{W}{Y_1}\right)$	Free	Nago(Spheerli and Hager 1999)
$C_d = 0.615\left(1+0.3\dfrac{W}{Y_1}\right)^{-1}$	Free	Cozzo(Spheerli and Hager 1999)
$C_d = 0.611\left(\dfrac{Y_1 - W}{Y2+15W}\right)^{0.072}$	Free	(Swamee 1992)
$C_d = 0.611\left(\dfrac{Y_1 - W}{Y2+15W}\right)^{0.072}\left(0.32\left(\dfrac{0.81Y_3\left(Y_3/W\right)^{0.72} - Y_1}{Y_1 - Y_3}\right)+1\right)^{-1}$	Submerged	(Swamee 1992)

In this Table C_d is discharge coefficient C_c is the contraction coefficient.

Therefore, selecting a discharge coefficient for the gate must be carried out with specific calibration of gate and supported ideally by validation (Lozano et al. 2009). Hence, to find the optimum coefficient for calibration of discharge equation, there are different methods, each has a specific error. The complexity of some equations and being time-consuming for field methods make it necessary to use intelligent methods as a substituent.

In the recent years, metaheuristic algorithms have been used in complex problems and optimization issue. The developed methods are routed in nature to solve optimization problem. The Simulated Annealing optimization method (SA) is a numerical optimization method with smart random structure which has been simulated based on annealing physical process. Some methods are formed from the study on social insects' behavior such as ant colony method (Jalali 2007). This research aims to review the Energy and Energy-Momentum methods in two algorithms of SA and continuous Ant Colony (ACO_R) along with intelligent methods in calibration of sluice gate in free and submerged flow.

2. Methods

In this research, the Energy equation of Rajaratnam snd Subramanya (1967) is used for free and submerged flow through sluice gate as in equations 1 and 2 obtained from the application of Energy equation for downstream and upstream flow and their discharge coefficients were calibrated (Fig. 1)

$$Q = C_d bW\sqrt{2gY_1} \quad \text{Free flow} \tag{1}$$

$$Q = C_d bW\sqrt{2g(\Delta Y)} \quad \text{Submerged flow} \tag{2}$$

In these equations b is gate width [L], g is gravity acceleration [L/T^2], ΔY is difference between upstream and downstream depth. The value of ΔY was obtained from Eq. (3) (the difference between upstream and downstream depth immediately after the gate (submerged depth) presented by Clemmens et al (2003) and Rajaratnam snd Subramanya (1967). Based on the equation, the value of discharge coefficient of submerged flow was calibrated using both Eq. (3) and (4) and the accuracy of each was investigated.

$$\Delta Y = Y_1 - Y_3 \tag{3}$$

$$\Delta Y = Y_1 - Y \tag{4}$$

Another method to calibrate the gate in submerged flow is the combined method of Energy-Momentum (Clemmens et al. 2003) in which Energy equation between section 1 and 2 is used due to ignoring Energy loss and Momentum equation is used in the range from section 2 to 3 due to hydraulic jump and energy dissipation. The mentioned method was used for calibration as the following. First, the gates of observational discharge Y_1 and Y_2 are inserted into Momentum Eq. (5) and the submersion depth is obtained.

$$\frac{q^2}{gY_2} + \frac{Y^2}{2} = \frac{q^2}{gY_3} + \frac{{Y_3}^2}{2} \tag{5}$$

In this equation q is the discharge value in the width unit of gate and the value of Y_2, is calculated from Eq. (6).

$$Y_2 = C_C.W \tag{6}$$

Inserting the values of the above equations in Eq. (7), we get q value.

$$Y_1 + \frac{q^2}{2g{Y_1}^2} = Y + \frac{q^2}{2g{Y_2}^2} \tag{7}$$

In these equations, Cc requiring calibration. One of the important bases of optimization and estimation of model parameters is to choose objective function. As gate discharge calibration aims to find experimental coefficients to calculate the discharge, these coefficients must be estimated in a way that there is a negligible difference between calculated discharge from theoretical equation and the

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observed discharge in practice. Therefore, using square sum of observed and calculated discharges as objective function for minimization can lead us to good solutions (Eq. 8).

$$OF = \sum_{i=1}^{n} \left(Q_{c,i} - Q_{o,i}\right)^2 \quad (8)$$

$Q_{o,i}$ is the values of observed discharge[L^3/T], $Q_{c,I}$ is the calculated discharge value obtained from Energy or Energy–Momentum methods, i is the counter n is the number of observations.

The decision variables for minimization of this function include flow coefficient for calibration of gate at free flow and submerged flow using Energy method and contraction coefficient for calibration using Energy–Momentum method. Optimization was carried out by simulate annealing and Ant colony optimization which were under sensitivity analysis in Matlab R2009a.

SA algorithm is a Metaheuristic algorithm which uses simulation of simulate annealing to calculate optimal value. The main idea of SA method was introduced by Metropolis et al (1953) without optimization content. Then, this idea was developed by Kirk patrik et al (1983) and Cerny (1985) independently for optimization and SA method became introduced.

Artificial ants introduced in 1991 by Colorni et al, artificial ants search a wide area with simulation of real ants foraging for food. They showed that the b q is the discharge value in the width unit of gate and Cc is the contraction coefficient behavior of food search in real ants can be adapted on optimization problems with small charges on which Ant Colony algorithm was developed. Dorigo (1992) developed the first algorithm to show the ants' behavior for food. With the assumption of continuous variable space, the algorithm is able to move on R space of real numbers. In ACO_R algorithm, the continuity of space in decision variables is carried out in a probability density function. (Socha and dorigo 2008).

In the present research, a rectangular flume of 12.5 m, 0.6 m, and 0.62m in length, width and height with a slope of 0.0002 equipped with a sluice gate and calibrated butterfly valve to measure discharge. The measurements of water level with point gauge of 0.1 mm accuracy were done. The data required for free flow and submerged flow were measured at 35 and 41 test series. These data include observed discharge, gate opening and upstream depth for all flow states in addition to downstream depths for submerged flow.

After the competition of tests and measurements, 70% were selected for calibration (optimization process) and 30% for validation of solutions randomly. In SA method, the quality of solutions is sensitive to the existing parameters and it is important to determine the parameters which produce suitable solutions. (Zegordi et al. 1995). The results of SA applications show that the computation time and the efficiency of this model depend on the setting of its parameters. (Kouvelis and Chiang 1992). Therefore, in this research, the algorithm of related problems underwent sensitivity analysis. Different parameters used to do sensitivity analysis are provided in Table 2.

The ACO_R algorithm is sensitive to the parameter change and to get the best solution, the algorithm must undergo sensitivity analysis using parameter change. The parameters influential which were changed in sensitivity analysis are in Table 3. The intensification factor (q), the positive number inversely related to the importance of good solutions (the inverse of pheromone concentration in that the less the concentration, the greater importance) and parameter ζ which is a positive coefficient influential on probe. In fact, this coefficient acts as the pheromone evaporation ratio. The less the coefficient, the faster the convergence. And it increases the probability of being trapped in local optimum. The great value of this coefficient makes the memory full and decreases the accuracy.

To do the calculations, the algorithms and the equations were written in a computer program along with parameters and objective function. All algorithms underwent the sensitivity analysis. As some parameters were dependent on each other, the sensitivity analysis and parameter change were done simultaneously. Based on sensitivity analysis, SA algorithm had a slower performance to convergence of solution meaning that there is need to more iterations to get the optimum solution, while continuous ant colony algorithm converges to the optimal solution in the initial iterations and algorithm run with great number of iterations increases the time without any effect in quality of solution. Therefore, ACO_R is allocated less time than SA algorithm due to faster convergence. In this research, the value differences of objective function obtained compared to parameter change in ACO_R is less than that in SA algorithm and objective function tolerance in sensitivity analysis was small showing a less sensitivity to parameter change. As seen, the minimum value of objective function and the coefficient of both algorithms are the same in all objective functions. The most optimum solution from SA algorithm and ACO_R for objective function with the most optimum setting case are presented in tables 4 and 5, respectively.

3. Results and discussion

Table 2. SA algorithm parameters and the tested values

Temperature update function	Annealing Function	Initial temperature	Max. iteration	Tolerance function	Reanneal interval
				0.000001	100
Exponential		100	500	0.00001	50
	Fast	50	400	0.0001	40
Linear		20	300	0.001	30
	Baltzmann	10	200	0.01	20
Logarithmic		5	100	0.1	10

Table 3. ACO algorithm parameters and tested values.

Initial population	New population	Max iteration	q	ζ
2	2	5	0.2	0.01
10	5	10	2	0.1
20	10	20	5	1
50		50		

Table 4. The values of objective function and coefficient of SA algorithm for the most optimum algorithm parameters.

Objective function	The best coefficient	The lowest objective function*10^3	Temperature update function	Annealing Function	Initial temperature	Max. iteration	Tolerance function	Reanneal interval
Conventional discharge Equation for sluice gate in Free flow	0.686	1.6367	Exponential	Fast	0.000001	300	100	40
Conventional discharge Equation for sluice gate In Submerged flow using Y	0.881	2.4315	Exponential	Fast	0.000001	300	100	50
Conventional discharge Equation for sluice gate In Submerged flow using Y_3	1.179	3.1314	Exponential	Fast	0.000001	200	100	40
Energy- Momentum method for Sluice gate in submerged flow	0.553	0.6915	Exponential	Fast	0.000001	300	100	40

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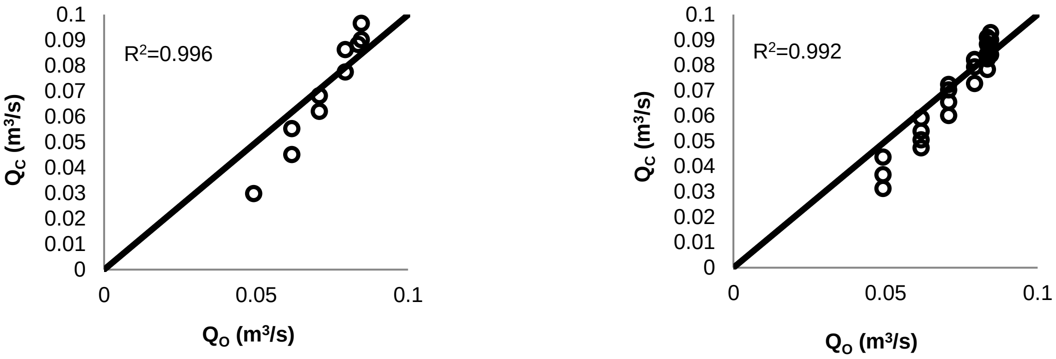
Table 5. The values of objective function and coefficient of ACO_R algorithm for the most optimum algorithm parameters.

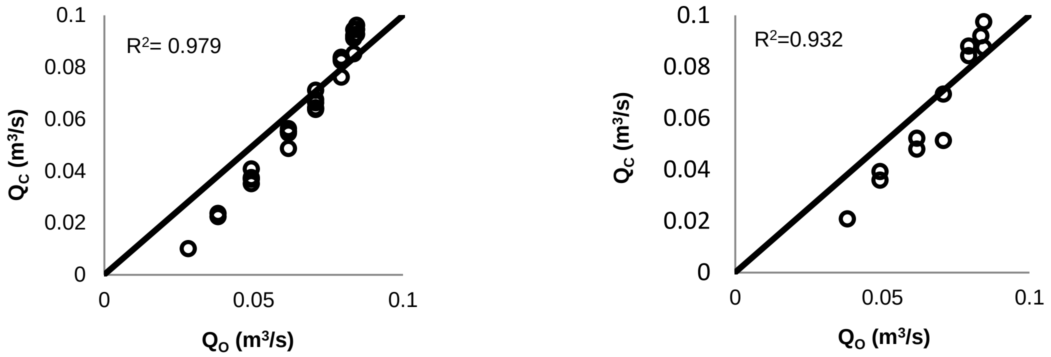
Objective function	The best coefficient	The lowest objective function*10^3	Initial population	New population	Max iteration	q	ζ
Conventional discharge equation for sluice gate in free flow	0.686	1.6367	10	5	5	0.2	1
Conventional discharge equation for sluice gate in submerged flow using Y	0.881	2.4315	10	10	5	0.2	1
Conventional discharge equation for sluice gate in submerged flow using Y_3	1.179	3.1314	2	10	5	0.2	1
Energy- Momentum method for sluice gate in submerged flow	0.553	0.6915	2	10	5	0.2	1



a. Calibration data

b. Validation data

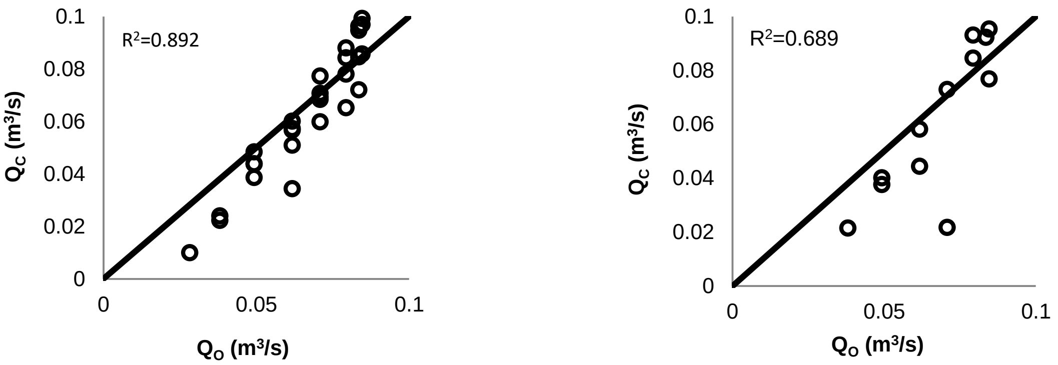
Fig. 2. Correlation diagram of Conventional discharge equation for sluice gate in free flow.



a. Calibration data

b. Validation data

Fig. 3. Correlation diagram of Conventional discharge equation for sluice gate in submerged flow using Y



a. Calibration data

b. Validation data

Fig. 4. Correlation diagram of Conventional discharge equation for sluice gate in submerged flow using Y3.

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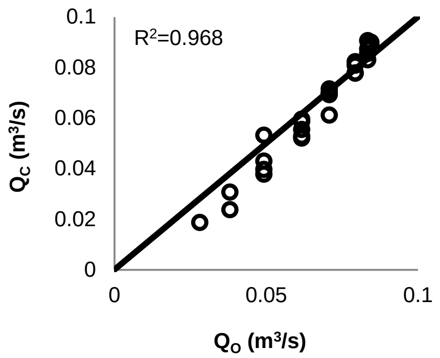
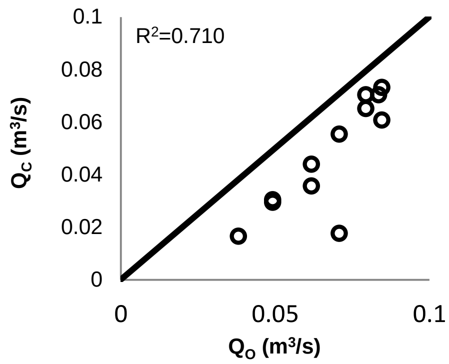


a. Calibration data



b. Validation data

Fig. 5. Correlation diagram of Energy-Momentum method for sluice gate in submerged flow.

Table 6. The equations of calculating statistical indexes to assess results.

Index	equation of calculating index
$R^2=\dfrac{\left[\sum_{i=1}^{n}\left(Q_{o,i}-\overline{Q_o}\right)\left(Q_{c,i}-\overline{Q_c}\right)\right]^2}{\sum_{i=1}^{n}\left(Q_{o,i}-\overline{Q_o}\right)^2\sum_{i=1}^{n}\left(Q_{c,i}-\overline{Q_c}\right)^2}$	Coefficient of Determination
$MBE=\dfrac{\sum_{i=1}^{n}\left(Q_{c,i}-Q_{o,i}\right)}{n}$	Mean Bias Error
$RMSE=\sqrt{\dfrac{\sum_{i=1}^{n}\left(Q_{c,i}-Q_{o,i}\right)^2}{n}}$	Root Mean Square Error
$E_r=\left\lvert\dfrac{Q_{o,i}-Q_{c,i}}{Q_{o,i}}\right\rvert*100$	Relative Error

In Figs (2) to (5), the correlation graphs of calibration data and validation of each objective function are presented separately. The value of the observed discharge is the length of points and the value of calculated discharge is the width of points based on the obtained coefficients. The index R^2 is a numerical criterion to make an assessment the closeness of which to one shows the favorability of solution. In these diagrams, it is seen that for validation data, discharge is underestimated. Since calculated and measured data are compared to assess the quality of solution from algorithm. In this research, to assess the results, some statistical indexes are used as in Table 6.

As the results of both algorithms are the same, the values of statistical indexes are simultaneously calculated as seen in Tables 7 and 8. Although all the indexes are located in an acceptable range, using calibrated coefficient for calibration data gives better results as the values of R^2 confirm the issue. Regarding the diagrams and indexes in the conventional discharge equation in submerged flow, using the difference between Y and Y_1 provides more accuracy than that of Y_1 and Y_3. In using the Energy-Momentum equation, it is seen that this method gives better results for calibration data. $\overline{E_r}$ is the mean of relative error percentage.

Table 7. The values of statistical indexes for calibration data.

Objective function	RMSE	MBE	$\overline{E_r}$
Conventional discharge equation for sluice gate in Free flow	0.0081	-0.0019	9.46
Conventional discharge equation for sluice gate In submerged flow using Y	0.0093	-0.0032	15.04
Conventional discharge equation for sluice gate In submerged flow using Y_3	0.0106	-0.0032	31.61
Energy- Momentum method for sluice gate in submerged flow	0.0063	-0.0026	9.49

Table 8. The values of statistical indexes for validation data.

Objective function	RMSE	MBE	$\overline{E_r}$
Conventional discharge equation for sluice gate in Free flow	0.0101	-0.0026	13.05
Conventional discharge equation for sluice gate In submerged flow using Y	0.0115	-0.0042	17.19
Conventional discharge equation for sluice gate In submerged flow using Y_3	0.0175	-0.0063	20.67
Energy- Momentum method for sluice gate in submerged flow	0.0232	-0.0204	32.58

In Figs. 6-9, the diagrams of relative error percentage (E_r) versus relative gate opening (W/Y_1) and that against calculated discharge have been shown for different methods of research, using the whole data. In these diagrams, to measure E_r, the equation in Table 6 has been used without absolute value. As seen in diagrams, the calibration of free flow with relative opening increase (W/Y_1), the relative error percentage decreases moving towards overestimation. While for most data, underestimation in discharge calculation has been observed. In the range medium discharges, there is seen to be less error. In addition, increasing discharge makes the relative error percentage proceed from underestimation for small discharges to overestimation for larger discharges. The submerged flow has the same procedure, except for the lack of specific correlation between relative opening and relative error percentage. In the methods used for submerged flow, most of the points have underestimation and the overestimation points in less relative opening are seen more. Point distribution and points with large relative error percentage on the relative opening diagram versus relative error percentage are greater than that of free flow, which is more visible for Energy-Momentum method diagram and the relative error percentage to observed discharge.

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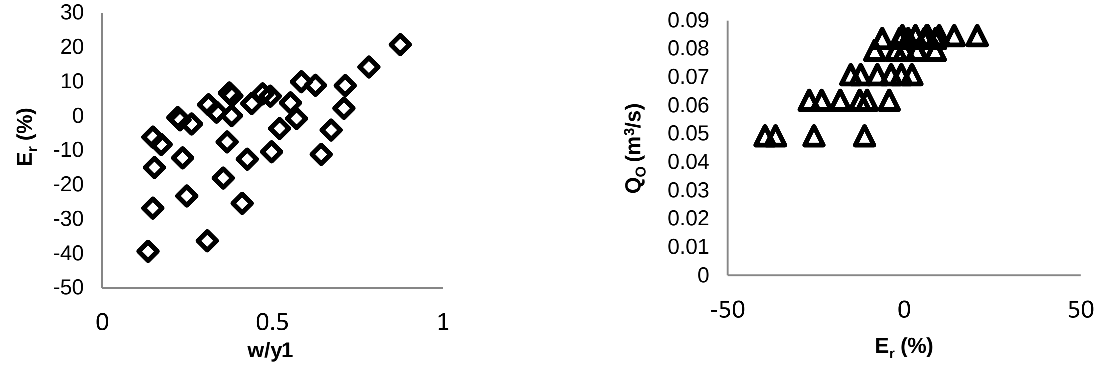
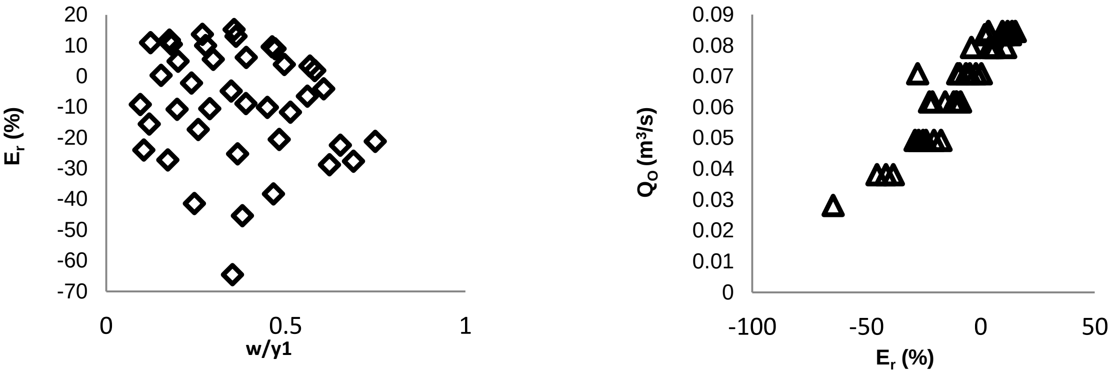


a .E_r versus relative opening

b. E_r versus observed discharge

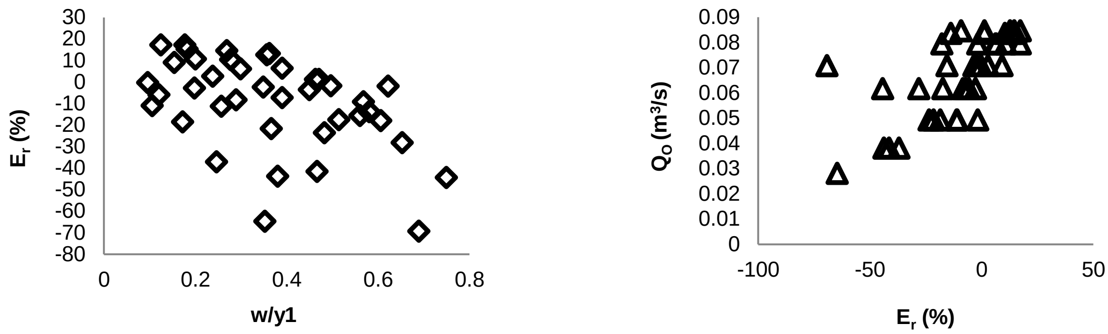
Fig. 6. Conventional discharge equation for sluice gate in free flow.



a .E_r versus relative opening

b. E_r versus observed discharge

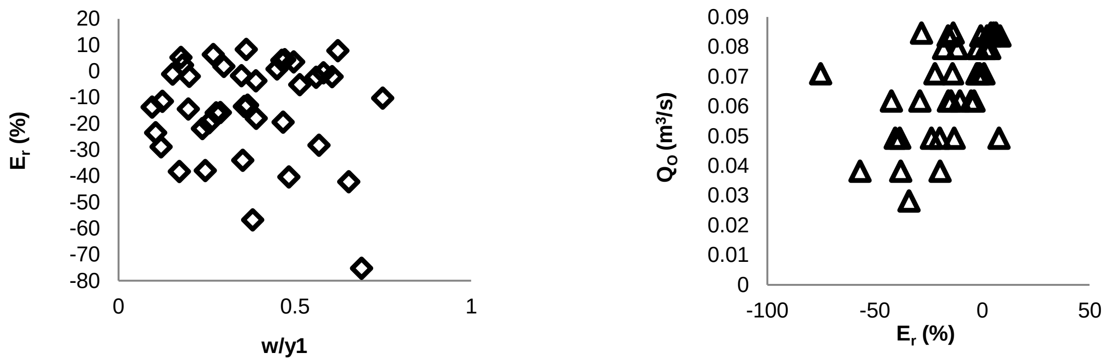
Fig. 7. Conventional discharge equation for sluice gate in submerged flow using Y.



a .E_r versus relative opening

b. E_r versus observed discharge

Fig. 8. Conventional discharge equation for sluice gate in submerged flow using Y3.



a .E_r versus relative opening

b. E_r versus observed discharge

Fig. 9. Energy- Momentum method for sluice gate in submerged flow.

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To compare the results of this research with those of previous researches, the data used in this research were placed in Table 1 and the coefficients were used to calculate discharge. Finally, two parameters R^2 and E_r were calculated for these equations and the methods presented in this research using all validation and calibration data. The results of these parameters are presented in Table 9. Regarding Table 9 about the free flow, the equation presented by Swamee has provided weak results for the present data while Noutsopoulos and Fanariotis's equation and Nago and Cozzo's have good R^2 index. Considering both R^2 index and $\overline{E_r}$ the present method has provided good results. For submerged flow, Swamee's equation has weak results and the conventional discharge equation for Y at downstream depth with high values of R^2 and low values of mean relative error percentage is used as the best method to calculate Discharge and calibration of sluice gate in submerged flow. Although the $\overline{E_r}$ is less in Energy-Momentum method showing the accuracy, the weak statistical indexes for validation data and low R^2 decrease the suitability of the method.

Table 9. Comparison of results of the previous equations with those of the present research for use in all data.

Presenter	Flow state	R^2	% Er_{mean}
(Rajaratnam. 1976)	free	0.81	22.19
(Garbrecht. 1977)	free	0.81	91.5
Noutsopoulos and Fanariotis(Spheerli and Hager 1999)	free	0.98	27.41
Nago(Spheerli and Hager 1999)	free	0.98	26.95
Cozzo(Spheerli and Hager 1999)	free	0.98	24.43
(Swamee. 1992)	free	0.11	82.63
Conventional discharge equation (This research)	free	0.93	10.49
(Swamee. 1992)	submerged	0.37	92.29
Conventional discharge equation using Y(This research)	submerged	0.96	15.68
Conventional discharge equation using Y_3(This research)	submerged	0.82	16.53
Energy- Momentum method	submerged	0.76	14.42

4. Conclusions

In the present research, there were attentions to calibration of sluice gate in free and submerged flow using two metaheuristic algorithms of SA and continuous ant colony. The target functions were defined using equations that researchers introduced before and the optimization was carried out with MATLAB R2009. The algorithms underwent sensitivity analysis to get most optimum solution. Finally, optimum coefficients for theoretical equations were obtained.

After completion of algorithms and sensitivity analysis, the optimum discharge coefficient of for conventional discharge equation in sluice gate for free flow is 0.686, in submerged flow with upstream depth difference (Y_1) and the depth immediately after gate (Y), is 0.881 and for upstream depth difference (Y_1) and downstream depth after(Y_3) perturbations was 1.179. Also, the contraction coefficient in Energy-Momentum method for submerged sluice gate was 0.533.

Regarding the analysis and calculation of statistical indexes, it can be seen that using Metaheuristic algorithms of SA and ACO_R can be suitable to calibrate the equations of sluice gate. Also, in calibration of submerged flow of sluice gate, using conventional discharge equation the better results can be obtained with upstream depth difference (Y_1) and depth after gate (Y). In addition, it was concluded that Energy-Momentum method can provide good results for data with it is calibrated, while the results of other data are weak yet acceptable.

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