Discharge Characteristics Through Vertical Sluice Gate in a Sudden Expanding Stilling Basin

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Abstract There is no doubt that, sluice gates are one of the most practical important controller and metric device. The discharge coefficient of sluice gate is an associating function of geometric and hydraulic parameters. The present study was focused on investigating experimentally the different parameters affecting the discharge below one vent sluice gate under free flow conditions. The impact of different expansion ratios and the effect of lateral sill on discharge characteristics have been investigated. Results show that, the augmentation in the expansion ratio yeve higher values for the discharge coefficient, the optimal design of lateral sill which led to high values of the discharge coefficient was also determined. Results of past studies which concerned of sluice gate discharge coefficient determinable were included for comparison purpose. The proposed statistical equations were compared with the laboratory statements and appear to be in a good agreement.

1 Introduction

Sluice gates are regarded one of the most important controllers of the flow through regulators. According to the downstream water level, sluice gates are classified into sluice gate discharging free and submerged flow. Due to the importance of the sluice gate as a control device in hydraulic engineering, the prediction of flow characteristics through gates has been investigated by a lot of researchers in the past, typical examples were investigated by (*Henry 1950; Henderson 1966; Rajaratnam* and *Subramanya 1967; Rajaratnam* and *Humphries 1982*) **[1-4]**.

Exactituded discharge coefficient equations for free and submerged flows were evolved along with the standard of free and submerged flow by (*Swamee 1992*) **[5]**. Experimental study on simulataneous flow over and under a sluice gate was carried out by **(***Ferro 2000*) **[6]**. (*Yen et al. 2001*) **[7]** studied the different characteristics of a vertical sluice gate in a rectangular channel of flatteened bed. Submerged radial gates were investigated by (*Clemmens et al. 2003*) **[8]**. Experimental and numerical studies on the characteristics of flow under normal sluice gates were investigated by (*Cassan* and *Belaud 2012*) **[9]. (***Ghodsian 2003*) **[10]** studied experimentally the hydraulic characteristics of a side sluice gate. It was showed that the discharge coefficient for the side sluice gate is relevant with Froude number and the ratio of upstream depth of flow to sluice gate opening for free flow. (*Khalili Shayan* and *Farhoudi 2013*) **[11]** derived an equation for gate's discharge coefficient in submerged condition with relative opening and relative tailwater depth. A formula for destining energy loss factor of sluice gate at free flow was also presented. (*Saudia 2014*) **[12]** studied experimentally and verified empirically the different parameters affecting the discharge through submerged multiple sluice gates (i.e, expansion ratios, gate operational management, etc.).

A general formula for the coefficient of discharge was envolved using multiple statstical regression of the laboratory results. Results showed that, the augmentation in the expansion ratio and the asymmetric gates operation lead to higher values for the coefficient of discharge. (*Habibzadeh et al. 2011*) **[13]** derived a formula using a theoretical method for the coefficient of discharge of sluice gates in rectangular channels under orifice-flow for both free and submerged conditions. The new equations can be utilized to expect the rendition of sluice gates with various edge shapes under free- and submerged-flow conditions. (*Mishra et al. 2013*) **[14]** introduced a useful study for refining the design of baffle-sluice irrigation module. Extant empirical relationships evidenced effectual to model the discharge. (*Kim 2007*) **[15]** showed that the numerical implements using the *RANS* formulae are enough developed to compute the contraction and the discharge coefficients, and the pressure distribution for a free flow past a sluice gate.

Artificial neural networks (*ANNs*) modelling method was employed by (*Rady 2016*) **[16]** to study the flow characteristics below vertical and inclined sluice gates for both free and submerged flow situations. Two *ANN* models were envolved resultantly two popularization equations to forecast the discharge coefficient (C_d) values. Results indicated that the *ANNs* are sturdy tools for modelling flow rates below the two types of sluice gates within an accurateness of ±5%. (*Rajratnam 1997*) **[17]** derived a formula for the coefficient of discharge of sluice gates in rectangular channels using theoretical method under both free and submerged situations. He concluded that the energy loss factor is a function of the gate geometries and may redound the discharge coefficient. (*Spulveda et al. 2009*) **[18]** explored various calibration methods for C_d of submerged sluice gates. (*Wu* and *Rajaratnam 2015*) **[19]** reconnoitred solutions to rectangular sluice gate flow problems. (*Belaud et al. 2009*) **[20]** Proposed a new theoretical method for the computation of the coefficient of contraction under sluice gates on flatten bed for both free and submerged situations. The contraction coefficient was varied with the relative gate opening and the relative submergence, particularly for large gate openings. (*Oskuia* and *Salmasi 2012*) **[21]** developed two equations, linear and nonlinear, to determine discharge coefficient by using dimensional analysis and linear and nonlinear regression analysis, for both free and submerged flow situatios. Results of past studies carried by various researchers appertaining sluice gate discharge coefficient delimiting were included for comparison purposes.

Sills located under gates is greatly utilized in irrigation structures to reduce the height of gate and consequently its weight, thus the required lifting force is minimized. Consequently the gate cost was reduced. Sills are provided also to stilling basin to increase the rate of energy dissipation, and to reside the hydraulic jump (*Hager 1992*) **[22]**. (*Ali* and *Mohamed* 2010) **[23]** investigated the impact of stilling basin of various shapes on the characteristics of submerged hydraulic jump. (*Mc Corquodale* and *Khalifa 1980*) **[24]** explored the characteristics of submerged hydraulic jump in a radial basin experimentally and theoretically. Based on flume investigation the characteristics of submerged flow under vertical gate with upstream sill of horizontal channel were analyzed by (*Negm et al. 2001*) **[25].** Polygonal sills with constant height, constant upstream slope and variable downstream slope were utilized under the gate. (*Negm 2000*) **[26]** compared the rendition of rectangular and radial stilling basins from both hydraulic jump and discharge characteristics point of views. The radial basin was found more efficient with respect to the whole characteristics. (*Negm 2000*) **[27]** analyzed the experimental results of subcritical flow under gate in radial basin with sill. A general equation for the discharge coefficient for the full range of submerged flow (supercritical, critical and subcritical flows) was advanced. (*Neveen 2011*) **[28]** investigated the effect of circular-crested sills with various radii under submerged vertical sluice gates on the discharge coefficients, in case of supercritical flow condition. A design chart was introduced to compute the discharge coefficient of circular-crested silled gates.

(*Ferro 2018*) **[29]** used the momentum equation for free flow condition in order to deduce the stage discharge relationship of a sharp crested sluice gate. Then, the theoretically deduced formula was titrated using experimental results obtained in olden studies. (*Abdelmonem et al. 2018*) **[30]** investigated the flow characteristics of the classical hydraulic jump by using a pendulum sill downstream of the sluice gate of the hydraulic structure. It increased the energy dissipation of the jump with about 20% and decreased the sequent depth ratio and the jump length.

(*Karami et al. 2019*) **[31]** applied the Flow-3D model to investigate the effect of the shape and height of the sill under a sluice gate on the hydraulic flow characteristics. The results showed that the shape and height of the sill under a sluice gate in free flow condition had a great effect in increasing the discharge coefficient of the sluice gate. (*Sunik 2019*) **[32]** investigated experimentally flow below sluice gate by using cubic baffle blocks and end sill to enhance the performance of the contraction coefficient and discharge coefficient. (*Parsaie et al. 2019*) **[33]** forecasted the discharge coefficient of combined weir-gate by using the artificial neural network (ANN), support vector machine (SVM) and adaptive neuro-fuzzy inference systems (ANFIS). Sensitivity analysis of applied models appeared that the ANN is the most sensitive model in comparison with others.

A theoretical formula was proposed by (*Li et al. 2018*) **[34]** to forecast variations of sluice gate discharge coefficient under free flow condition. Impacts of factors on discharge coefficient were also studied. The model can also be used to forecast the rendering of sluice gates with different sizes under free-flow conditions. (*Salmasi et al. 2019*) **[35]** investigated the effect of variable sill shapes and their geometric parameters on the discharge coefficient (C_D) of radial gates in a free flow condition. Results showed that they have a significant impact on C_D. Regression equations were also introduced.

A new form for the equation used to compute C_d was proposed by (*Balouchi* and *Rakhshandehroo 2018*) **[36]** which is based on a combination of triangular sharp-crested weir and four combined structures consisting of the weir and rectangular gates.

Investigation of discharge characteristics below gates is regarded one of the classical problems in hydraulic. Effect of performance of the stilling basin on the The discharge characteristics of gates was still poorly investigated. So, this research investigates experimentally effect of the performance of protected sudden expanding stilling basin of one vent regulator of free flow vertical gate on the discharge coefficient. The discharge characteristics of gate for different expansion ratios, different relative positions of lateral sill, and different relative height of sill were investigated. Dimensional analysis equations are also developed to predict the coefficient of discharge under free flow conditions for sluice gate using linear regression analysis.

2 Theoretical Approach

Figure 1 shows a definition sketch of one – vent regulator of sudden expanding stilling basin operating under free flow condition. The variables considered were as following b = sluice gate length, B = channel width, g = gravitational acceleration, G = sluice gate opening height, H_u = upstream water depth, h_x = sill height, L_x = the sill position measured from the gate opening, L = the apron length from the gate opening, y_1 = initial water depth of the hydraulic jump, ρ = density of water, and μ = dynamic viscosity of water.

A dimensional analysis is applied to obtain a physical function relation between the unit discharge and the different parameters of the gate and stilling basin. The functional relationship of the discharge per unit width (q) may be expressed as following:

$$f(q, G, g, B, b, H_u, h_x, L_x, L, y_1, \rho, \mu) = 0.0 \qquad (1)$$

Applying π- theorem and taking ρ, g and G as the independent variables and by neglecting μ, equation (2) was deduced.

$$\frac{q}{G^{1.5}\sqrt{2g}} = f\left(\frac{B}{b}, \frac{H_u}{G}, \frac{L_x}{L}, \frac{h_x}{y_1}\right) \qquad (2)$$

In which the term $\frac{q}{G^{1.5}\sqrt{2g}}$ represents the discharge coefficient of gate under free condition flow (C_d), e = expansion ratio ($e = B/b$). Then Eq. (2) can be inscribed as following:

$$C_d = f\left(e, \frac{H_u}{G}, \frac{L_x}{L}, \frac{h_x}{y_1}\right) \tag{3}$$

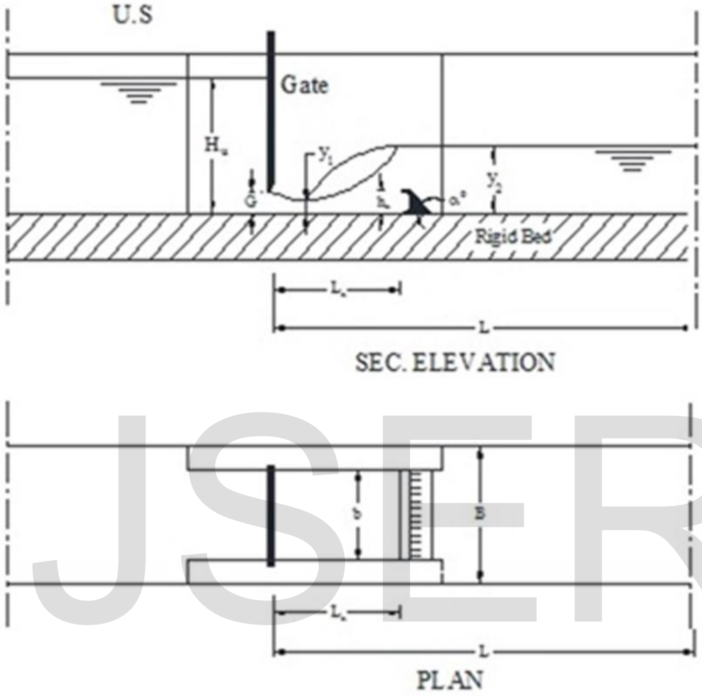


Fig. 1 Definition sketch of the model

3 Experiments

The experimental work was carried out at the hydraulic lab in the faculty of engineering, zagazig university. Experiments were accompanied in a re-circulating flume of 0.30 m wide; 0.50 m deep with an overall length of about 15.6 m with working section of 12 m. The discharge values were measured using pre-calibrated orifice meter fixed in the flow line. The water depths were measured by means of point gauge. The experimental model consisted of two abutments made from wood with a length of 60 cm. A control sluice gate is made from perspex of thichness 6 mm. This gate was utilized to control the upstream water depth and the gate opening. Over one hundred eighty runs (188 runs) were performed by adjusting the flow discharge with desired gate opening under free flow conditions. After approximately 15 min., the flow reached steady state condition, the discharge was adjusted to the desired value and the gate was opened to the desired opening for the required flow conditions. The ranges of experiments were as follows: H_u = 16-35 cm, and G = 2-5 cm.

A timber curved vertical sill model was fixed at the mid width of the floor body downstream the vertical gate. The experimental program can be summerized as follows:

1. The first set of experiments were executed to study the effect of expansion ratios on discharge characteristics. Five expansion ratios were tested (e = 1.25, 1.5, 1.76, 1.92 and 2.73).
2. Then, the effect of four positions of sill under expansion ratios (e = 1.25 and 1.5) were tested to explore the effect of sill location on discharge characteristics, their positions were varied as (L_x/L = 0.2, 0.3, 0.4 and 0.5).
3. For each position, Four relative heights of sill (h_x/y_1 = 0.5, 0.75, 1.0 and 1.25) were tested under expansion ratios (e = 1.25 and 1.5) to explore the most suitable height of the sill that improve the discharge characteristics.

4 Results and Discussion

4.1 Effect of expansion ratio (e) on the discharge coefficient

Figure 2 shows the relationship between the relative upstream water depth H_u/G and the discharge coefficient C_d for all expansion ratios e = 1.25, 1.5, 1.76, 1.92 and 2.73. It is noticed that, the discharge coefficient C_d increases slightly with the increase of the relative upstream water depth H_u/G for different expansion ratios. Also, the discharge coefficient C_d increases noticeably with the increase of the expansion ratio e. Because as the expansion ratio e increases, the flow passes through a limited width of channel, the velocity passing through the gate increases, the actual unit discharge increases, and hence the coefficient of discharge C_d increases. At free flow condition Table 1 shows the range of C_d values for different expansion ratios e. It is notable that the water way of irrigation channels always must be in range between 60% to 80%. So, the expansion ratios of $e > 1.5$ is not acceptable in practical design. The expansion ratios of (e = 1.25 and 1.5) are which practically occurs in design of irrigation channels. Then only the values of (e =1.25 and 1.5) will be selected and examined from peactical point of view.

On the other hand, Fig. (3) illustrates the relationship between C_d with H_u/G for (e = 1.25 and 1.5) in the present study and compare for with the previous results which obtained by (*Henry 1950*) **[1]** on free flow vertical sluice gate which is considered the most extensive and reliable. It is also compared with the discharge coefficient equation for free flow condition that was developed by (*Swammee 1992*) **[5]**. As shown in the mentioned figure, there is an acceptable agreement between the results of the present study for (e = 1.5) and those obtained by (*Swammee 1992*) **[5]**. The present study discharge coefficients were less than the discharge coefficients that were conducted by (*Henry 1950*) **[1]**. This variation may be due to the effect of two dead zones downstream sudden expanding stilling basin and the effect of water way contractions.

Table 1 Range of (C_d) values for different expansion ratios (e).

Expansion ratios (e)	Range of (C_d) values
1.25	0.501-0.553
1.5	0.510-0.577
1.76	0.525-0.622
1.92	0.499-0.647
2.73	0.657-0.774

Based on the experimental data and using the statistical regression analysis, for different expansion ratios, several models were proposed and their regression coefficients were estimated. Out of all trials, the average best empirical equation predicting the coefficient of discharge C_d, is developed in the following form:

$$C_d = 0.301 + 0.006\left(\frac{H_u}{G}\right) + 0.122(e) \tag{3}$$

(Coefficient of determination (R^2) =86%, *RMSE* =0.0007)

Fig.(4) shows a comparison between the measured values of the coefficient of discharge C_d and predicted one using equation 3. Fig.(5) shows the residuals of the statistical equations versus the predicted values.

4.2 Effect of lateral single sill on the discharge coefficient

Figs. 6 and 7 present variation of C_d against H_u/G for different positions of lateral single sill L_x/L = 0.2, 0.3, 0.4 and 0.5 under expansion ratios (e = 1.25 and 1.5) respectively. As it can be seen that, there is a marked variation in C_d values for different locations of lateral sill, under different expansion ratios. It is obvious that, at free flow conditions, the sill position L_x/L = 0.4 produces maximum values of the discharge coefficient under variable expansion ratios e compared to the other positions and no-sill case, the impact of the flow jet with the sill in the recirculation of jump in the roller zone is at the minimal value at position L_x/L = 0.4, consequently, the back flow was limited and the sill friction was very low and the coefficient of discharge was increased. The discharge coefficient increased by about 23% and 26% for e = 1.25 and 1.5, respectively, in comparison with the case of no sill.

Figs. (8 and 9) show the relationship between C_d and H_u/G for different relative heights of lateral single sill h_x/y_1 = 0.5, 0.75, 1.0 and 1.25 under different expansion ratios (*e* = 1.25 and 1.5) and the relative sill position was fixed at L_x/L = 0.4. It is clear that, for different values of *e* the maximum values of discharge coefficient occurred at sill height h_x/y_1 = 0.75. The discharge coefficient increased by about 32% and 36% for *e* = 1.25 and 1.5, respectively, in comparison with the case of no sill. The presence of the lateral sill downstream the gate works as a submerged weir in the waterway, so it leads to make changes in water levels, these changes increase with big heights and vice versa. Whenever the sill height increase, the flow bounced toward upstream direction then it works as an obstruction to the flow of water and this leads to increase the velocity of water above the sill to help drain the water behind the gate. Small heights may have a limited impact on the flow characteristics and for this reason the in between height h_x/y_1 = 0.75 may be the best. This height h_x/y_1 = 0.75 appears good agreeableness with average velocity flow and actual discharge, which is closely related to the coefficient of discharge C_d.

It is noted as shown in the mentioned figures that, the values of C_d increase slightly for the expansion ratio of (*e* = 1.5) compared to (*e* = 1.25). Table 2 shows the range of C_d values and the rate of increase in C_d for the optimum design of single lateral sill under variable expansion ratio *e*.

According to the Egyptian practice the sill height must not exceed 0.25 of gate height.

By statistics regression analysis, the verage best empirical equation predicts the coefficient of discharge C_d at expansion ratios (*e* = 1.25 and 1.5) can be put at the following form:

$$C_d = 0.302 + 0.0064\left(\frac{H_u}{G}\right) + 0.117(e) + 0.123\left(\frac{L_x}{L}\right) - 0.027\left(\frac{h_x}{y_1}\right) \qquad (4)$$

(Coefficient of determination (R^2) = 0.67, *RMSE* = 0.0004)

This equation is valid within the following ranges of the involved parameters C_d = [0.5-0.77], H_u/G = [4.8-10.97], *e* = [1.25-1.5], L_x/L = [0.2-0.5], h_x/y_1 = [0.5-1.25].

Fig.(10) shows a comparison between the measured values of the coefficient of discharge C_d and predicted one using equation 4. Fig.(11) shows the residuals of the statistical equations versus the predicted values.

Table 2 Ranges of (C_d) values and the rate of increase in (C_d) for the optimum design of single lateral sill under variable expansion ratio (e)

Expansion ratios (e)	Range of (C_d) values	Opimum sill dimensions	% Increase of (C_d)
1.25	0.532-0.630	(L_x/L=0.4, h_x/y_1=0.75)	32
1.5	0.563-0.653	(L_x/L=0.4, h_x/y_1=0.75)	36

5 Conclusions

Study of free flow condition through vertical sluice gate was presented and discussed based on an experimental investigation. The following conclusions were drawn:

- The values of discharge coefficient C_d increased noticeably as the relative upstream water depth H_u/G and the expansion ratios e were increased.
- Experimental results were compared with other published results and were consistent with results of Swamee's formula.
- The use of lateral sill of the best dimensions (L_x/L = 0.4, h_x/y_1 = 0.75) yielded to increase the discharge coefficient under vertical sluice gate by about 32% and 36% for (e = 1.25 and 1.5) respectively.
- Statistical models were developed using multiple linear regression to predict the C_d values. The proposed statistical equations were compared with the experimental data and appear to be in a good agreement.

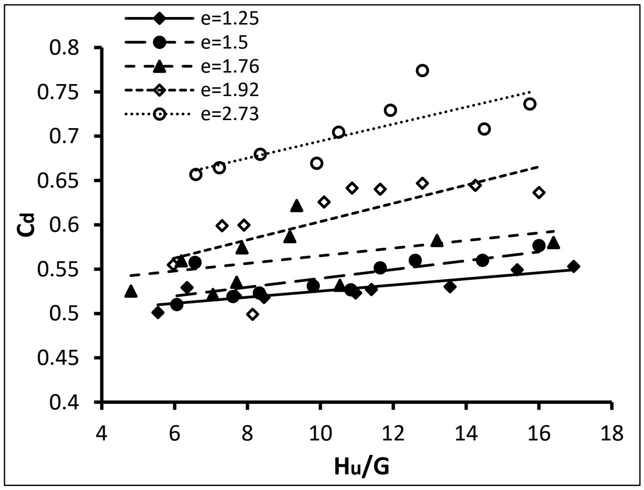


Fig. 2 Relationship between H_u/G and C_d for Different expansion ratios.

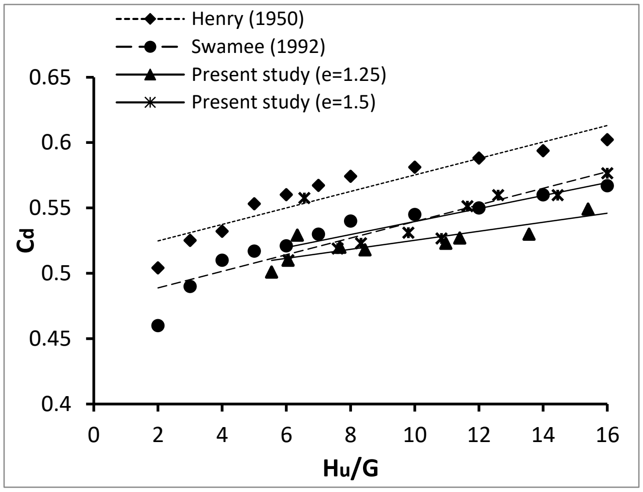
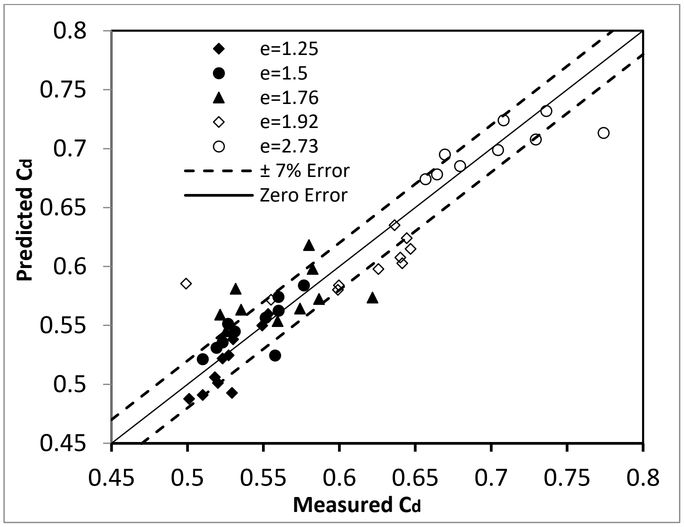


Fig. 3 Experimental values of C_d with those of Henry (1950) and Swamee (1992).



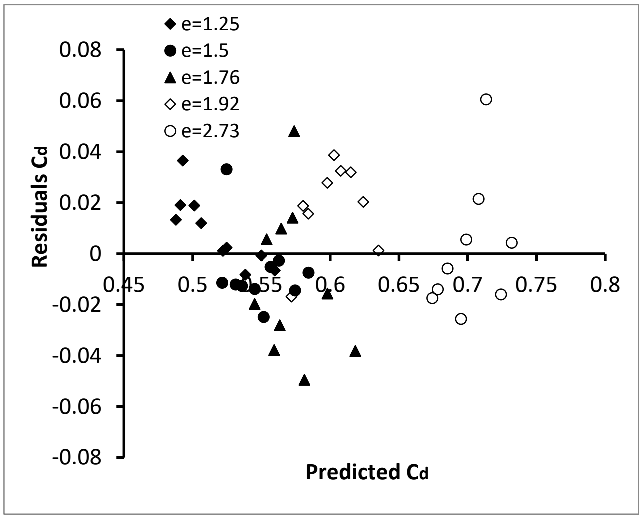
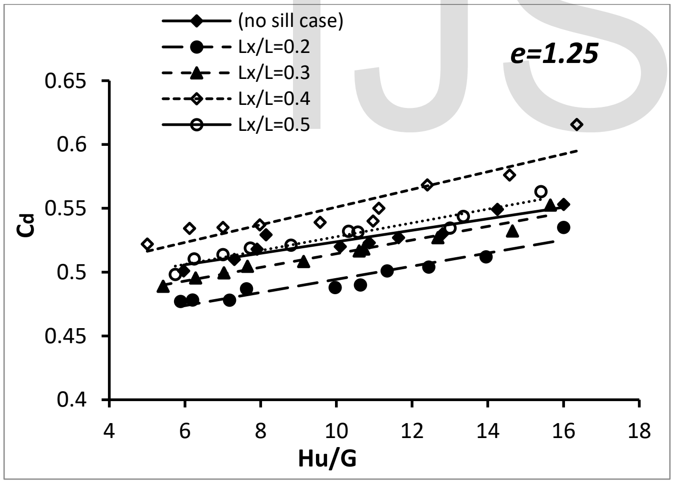


Fig. 4 Comparison between predicted and measured values of C_d for different values of *e*.

Fig. 5 Comparison between predicted and residuals for C_d for different values of *e*.



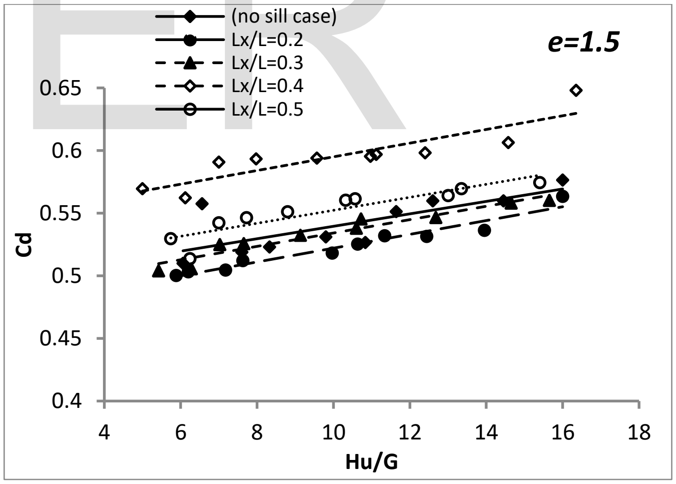


Fig. 6 Relationship between H_u/G and C_d for different sill positions at *e* = 1.25.

Fig. 7 Relationship between H_u/G and C_d for different sill positions at *e* = 1.5.

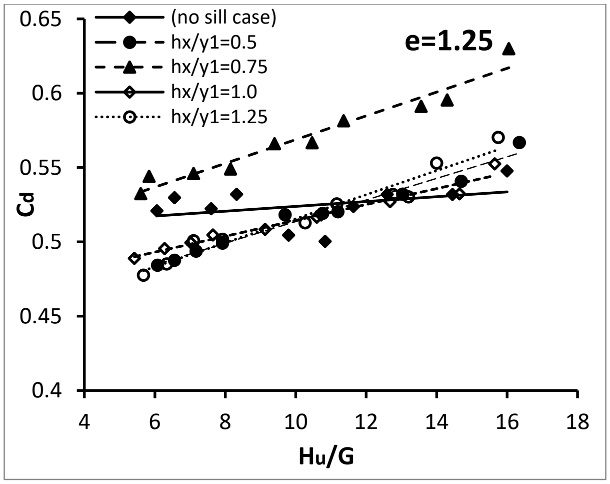


Fig. 8 Relationship between H_u/G and C_d for different sill heights at *e* =1.25.

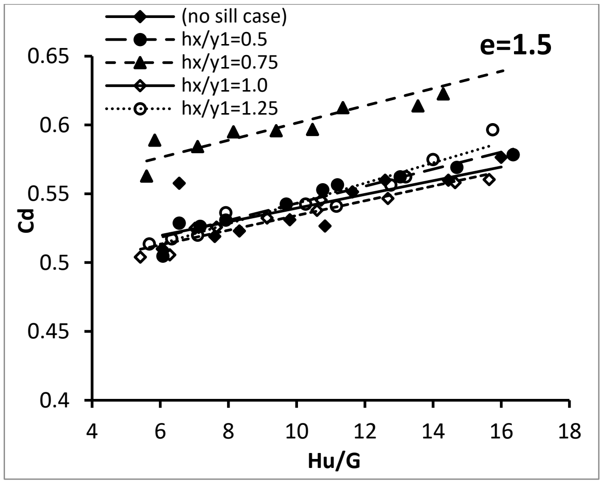


Fig. 9 Relationship between H_u/G and C_d for different sill heights at *e* =1.5.

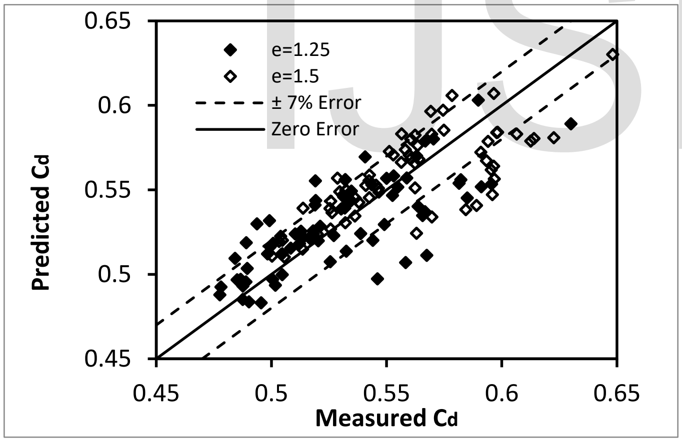


Fig. 10 Comparison between predicted and measured values of C_d for different sill dimensions.

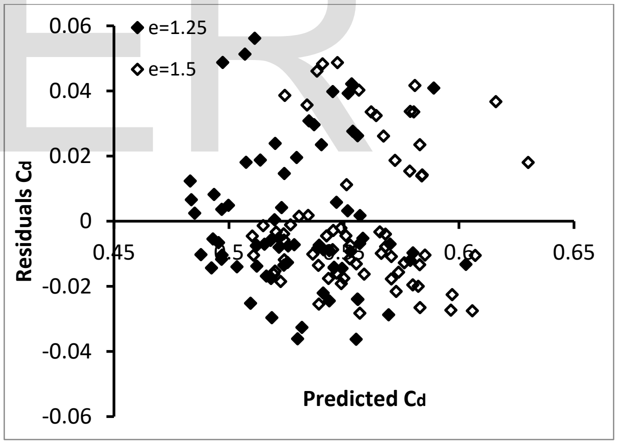


Fig. 11 Comparison between predicted and residuals for C_d for different sill dimensions.

NOTATIONS

b	sluice gate length (L)
B	channel width (L)
C_d	the discharge coefficient (-)
e	the expansion ratio, B/b (-)
g	gravitational acceleration (LT^{-2})
G	sluice gate opening height (L)
H_u	the upstream water depth (L)
h_x	the sill height (L)
L_x	the sill position measured from the gate opening (L)
L	the apron length from the gate opening (L)
q	the discharge per unit width (L^2T^{-1})
Q	the total discharge (L^3T^{-1})
y_1	initial water depth of the hydraulic jump (L)
y_2	sequent water depth of the hydraulic jump (L)
ρ	density of water (ML^{-3})
ρ_s	density of bed material (ML^{-3})
μ	dynamic viscosity of water ($ML^{-1}T^{-1}$)
R^2	coefficient of multiple determination
ANNs	Artificial neural networks
RMSE	root mean square error
RANS	Reynolds AveragingNavier-Stokes.

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