Analysis of Rectangular Side Sluice Gate

By Prabhata K. Swamee,[1] Santosh K. Pathak,[2] and Masoud S. Ali[3]

Abstract: A side sluice gate is a flow-regulation device widely used in irrigation works for diverting the flow from a main channel to a secondary channel. The discharge of a side sluice gate may be obtained through the concept of an elementary discharge coefficient for an elementary strip along the gate length. Similar to the case of a normal sluice gate, the elementary discharge coefficient for a side sluice gate has been found to be a function of channel flow depth to the gate opening ratio for free-flow conditions. It depends on an additional parameter, namely, the ratio of the crest width to the gate opening for submerged-flow conditions. For a broad-crested side sluice gate, the discharge coefficient involves still one more parameter: the ratio of the crest width to the gate opening.

INTRODUCTION

A side sluice gate is a rectangular opening (created by a vertical sliding gate) in the side of a channel through which lateral outflow into a side channel takes place. Side sluice gates are widely used as head regulators for canals, branches, silt flushing in a power canal forebay, and so on. Flow through a side sluice gate is governed by the equation of spatially varied flow with decreasing discharge.

A review of literature indicated that little attention has been given to the study of flow through side sluice gates, in spite of their great practical importance. Nougaro et al. (1975) studied diversion of flow with sluice gates at the end of main and side channels. Sluice-gate discharges have been studied for various gate openings. Panda (1981) and Tanwar (1984) related the discharge coefficient to the Froude number, the ratio of flow depth to the side sluice gate opening, and the ratio of tailwater depth to the side sluice gate opening. Hager (1983) and Hager and Volkart (1986) proposed the following equation for discharge variation along the side sluice gate for a prismatic nearly horizontal rectangular channel:

$$\frac{dQ}{dx} = \frac{a}{H}\left[\frac{2g}{3(4H - 3y)}\right]^{0.5} \quad (1)$$

in which a = gate opening; H = specific energy; y = flow depth; g = gravitational acceleration; and dQ/dx = discharge variation along the channel length.

In the present study, the concept of a discharge coefficient for an elementary strip along the side sluice gate (see Fig. 1) is introduced. A methodology based on numerical solution of two coupled ordinary differential equations for discharge and flow depth is proposed. The expressions for the elementary discharge coefficient have been obtained for both free- and submerged-flow conditions. These expressions have also been extended to cover the case of a broad-crested side sluice gate. Using the proposed meth-

[1]Prof. of Civ. Engrg., Univ. of Roorkee, Roorkee-247667, India.
[2]Prof. of Civ. Engrg., Univ. of Roorkee, Roorkee-247667, India.
[3]Res. Fellow, Civ. Engrg. Dept., Univ. of Roorkee, Roorkee-247667, India.

Note. Discussion open until May 1, 1994. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on May 26, 1992. This paper is part of the *Journal of Irrigation and Drainage Engineering*, Vol. 119, No. 6, November/December, 1993. ©ASCE, ISSN 0733-9437/93/0006-1026/$1.00 + $.15 per page. Paper No. 4128.

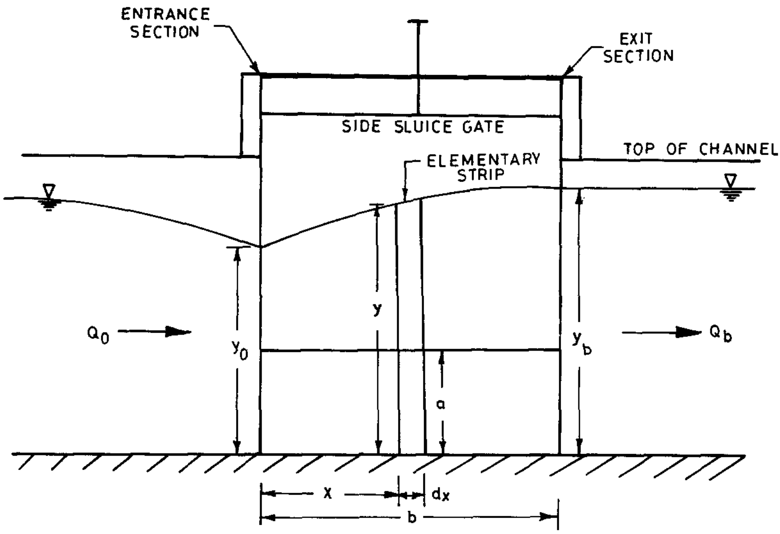

FIG. 1. Definition Sketch

odology and the expression of elementary discharge coefficient, the discharge and the flow profile along the side sluice gate can be accurately determined.

ANALYTICAL CONSIDERATIONS

For the flow through a side sluice gate, the governing differential equation for a rectangular prismatic channel is (Chow 1959)

$$\frac{dy}{dx} = \frac{S_0 - S_f - \dfrac{Q}{gA^2}\dfrac{dQ}{dx}}{1 - \dfrac{Q^2T}{gA^3}} \quad (2)$$

in which S_0 = channel bed slope; S_f = friction slope; Q = channel discharge; A = flow area; and T = top width of channel.

Eq. (2) assumes insignificant energy loss from flow diversion. For subcritical flow (2) indicates that there is normally a rising flow profile.

Considering the discharge dQ through an elementary strip of length dx along the sluice gate (see Fig. 1), one gets

$$\frac{dQ}{dx} = -C_e a\sqrt{2gy} \quad (3)$$

in which C_e = elementary discharge coefficient of the strip.

The friction slope S_f is given by the Manning's equation as

$$S_f = \frac{Q^2n^2}{A^2R^{4/3}} \quad (4)$$

in which n = roughness coefficient; and R = hydraulic radius.

For a rectangular channel section of bed width B, substitution of (3) and (4) into (2) yields

$$\frac{dy}{dx} = \frac{S_0 - \dfrac{Q^2 n^2}{B^2 y^{10/3}}\left(1 + \dfrac{2y}{B}\right)^{4/3} + \dfrac{QC_e a}{B^2 y}\sqrt{\dfrac{2}{gy}}}{1 - \dfrac{Q^2}{gB^2 y^3}} \quad \text{(5)}$$

Eqs. (3) and (5) can be solved as an initial-value problem with the following prescribed conditions: At $x = 0$

$$y = y_0 \quad \text{(6a)}$$

and

$$Q = Q_0 \quad \text{(6b)}$$

in which y_0 = flow depth at the entrance section; and Q_0 = entrance-section discharge. For the solution of (3) and (5) one requires the functional relationship for C_e.

ELEMENTARY DISCHARGE COEFFICIENT FUNCTION

Since (5) incorporates the effects of S_0, n, and the channel geometry, the elementary discharge coefficient C_e may be assumed to be a function of flow depth y and the side sluice gate opening a for free-flow conditions. For submerged-flow conditions, the tailwater depth, y_t in the side channel, is an additional parameter having considerable influence on C_e. Adopting the expressions proposed by Swamee (1992), the functional form of C_e for free flow through a sharp-crested side sluice gate is

$$C_e = k_0\left(\frac{y - a}{y + k_1 a}\right)^{k_2} \quad \text{(7)}$$

whereas for the submerged-flow condition, the functional form is

$$C_e = k_0\left(\frac{y - a}{y + k_1 a}\right)^{k_2}\left\{k_3\left[\frac{k_4 y_t\left(\dfrac{y_t}{a}\right)^{k_5} - y}{y - y_t}\right]^{k_6} + 1\right\}^{-k_7} \quad \text{(8)}$$

in which k_0 through k_7 = unknown positive constants to be determined from experimental data.

EXPERIMENTS

Experiments on a side sluice gate were conducted in a horizontal main channel (9 m long and 0.5 m wide) having, at its midlength, a right-angled side channel (2.75 m long and 0.5 m wide). A steel side sluice gate of lip thickness c was installed at the upstream end of the side channel flush with the main channel wall. Both the main and side channels were cement plastered and provided with tail gates at their downstream ends. A schematic view of the experimental setup is given in Fig. 2. The discharges through the side sluice gate and the main channel were measured by calibrated rectangular weirs. The water temperature was also noted in order to apply

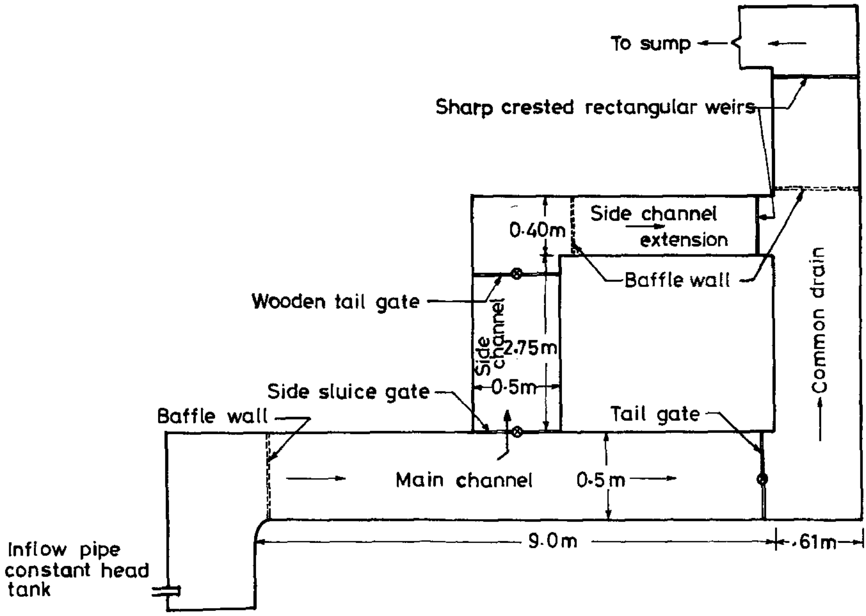

FIG. 2. Schematic Plan View of Experimental Setup

TABLE 1. Range of Parameters Studied

Variable (1)	PRESENT STUDY: Sharp Crested: Free flow (2)	PRESENT STUDY: Sharp Crested: Submerged flow (3)	PRESENT STUDY: Broad Crested: Free flow (4)	PRESENT STUDY: Broad Crested: Submerged flow (5)	Panda (1981) (6)
Q_0 (m³/s)	0.014–0.097	0.007–0.097	0.010–0.087	0.007–0.09	0.016–0.13
Q_s (m³/s)	0.006–0.09	0.003–0.094	0.003–0.055	0.0015–0.06	0.005–0.097
y_0 (m)	0.06–0.38	0.07–0.40	0.070–0.390	0.075–0.40	0.29–0.70
y_t (m)	—	0.05–0.40	—	0.06–0.40	—
a (m)	0.01–0.10	0.01–0.10	0.01–0.10	0.01–0.10	0.01–0.08
c (m)	0.002	0.002	0.05–0.15	0.05–0.15	0.002
c/a	0.02–0.2	0.02–0.2	0.5–15.0	0.5–15.0	0.025–0.2
y_0/a	1.50–33.0	1.25–35.0	1.60–34.0	1.40–36.0	3.60–66.0
y_t/a	—	0.315–29.0	—	0.5–30.0	—
B/b	1	1	1	1	1–1.6
F_0	0.02–0.8	0.025–0.89	0.03–0.80	0.04–0.85	0.05–0.40
Number of runs	70	170	125	314	105

discharge corrections for viscosity and surface tension (Kindsvater and Carter 1957). Diversion of flow into the side channel was smooth, with no significant turbulence at the entrance and exit sections. Water depths along the side sluice gate were measured at the centerline of the main channel with a point gage having an accuracy of ± 0.1 mm. Experiments were carried out for various combinations of side-sluice-gate opening and entrance water depth

y_0 for free-flow conditions. For submerged-flow conditions the tailwater depth y_t in the side channel was varied to obtain various degrees of submergence. Subcritical flow was maintained in both the main and side channels throughout all experiments. Table 1 gives the range of various parameters covered in the present study.

DETERMINATION OF CONSTANTS

For a given run, (3) and (5) were solved by a fourth-order Runge-Kutta method subjected to the initial condition of (6) at the inlet section ($x = 0$) and using trial values for the constants k_0 through k_7 in (7) and (8). The solution gave the computed values of water depth and discharge at various x-values along the side sluice gate and ultimately yielded the computed values of water depth y_{bi} and the discharge Q_{bi} at the exit section $x = b$. The computed discharge Q_{sci} through the side sluice gate was obtained by

$$Q_{sci} = Q_{0i} - Q_{bi} \quad \text{(9)}$$

where Q_{0i} = observed discharge at the inlet section for the ith run.

The computed side-sluice-gate discharge Q_{sci} was then compared with the observed discharge Q_{soi} to yield the percentage error ε as

$$\varepsilon = 100\,\frac{Q_{sci} - Q_{soi}}{Q_{soi}} \quad \text{(10)}$$

The average percentage error E for all the experimental data may be expressed as

$$E = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{Q_{sci} - Q_{soi}}{Q_{soi}}\right| \quad \text{(11)}$$

in which N = total number of runs. The average percentage error E is a function of the constants k_0 through k_7. Using a grid-search algorithm, E was minimized to yield the following best-fit results of (7) and (8), respectively:

$$C_e = 0.611\left(\frac{y - a}{y + a}\right)^{0.216} \quad \text{(12a)}$$

$$C_e = 0.611\left(\frac{y - a}{y + a}\right)^{0.216}\left\{0.24\left[\frac{2.5y_t\left(\frac{y_t}{a}\right)^{0.2} - y}{y - y_t}\right]^{0.67} + 1\right\}^{-1} \quad \text{(12b)}$$

The average percentage errors of the entire set of experimental data in the present study leading to (12*a*) and (12*b*) are 5.56 and 5.5, respectively. Fig. 3 depicts plots of (12*a*) and (12*b*).

For broad-crested side sluice gates, the coefficients k_0, k_3, and k_4 were found to be functions of c/a as

$$k_0 = 0.611\left(1 + 0.0112\,\frac{c}{a}\right) \quad \text{(13a)}$$

$$k_3 = \frac{0.24}{1 + 0.05\,\frac{c}{a}} \quad \text{(13b)}$$

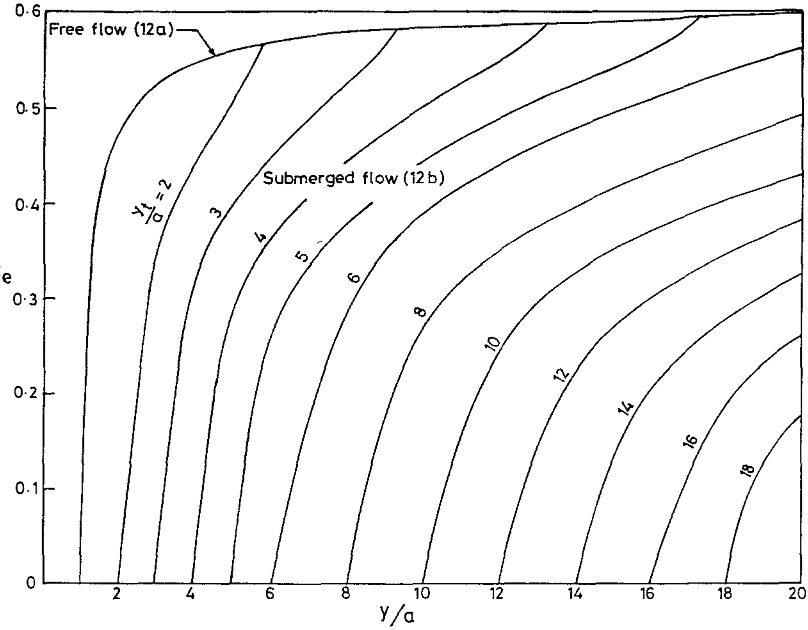

FIG. 3. C_e for Sharp-Crested Side Sluice Gate

and

$$k_4 = 2.5\left(1 + 0.0188\frac{c}{a}\right) \quad \text{(13c)}$$

whereas k_1, k_2, k_5, k_6, and k_7 remained the same as for the sharp-crested sluice gate. Incorporating (13*a*)–(13*c*) in (7) and (8), the respective elementary discharge coefficients for free and submerged flow become

$$C_e = 0.611\left(1 + 0.0112\frac{c}{a}\right)\left(\frac{y-a}{y+a}\right)^{0.216} \quad \text{(14a)}$$

$$C_e = 0.611\left(1 + 0.0112\frac{c}{a}\right)\left(\frac{y-a}{y+a}\right)^{0.216} \cdot \left\{\frac{0.24}{1 + 0.05\frac{c}{a}}\left[\frac{2.5\left(1 + 0.0188\frac{c}{a}\right)y_t\left(\frac{y_t}{a}\right)^{0.2} - y}{y - y_t}\right]^{0.67} + 1\right\}^{-1} \quad \text{(14b)}$$

As $c \rightarrow 0$ (which corresponds to sharp-crested side sluice gate) (14*a*) and (14*b*) reduce to (12*a*) and (12*b*), respectively. A comparison of (12*a*) and (14*a*) indicates that in the case of the free-flow condition for the sluice-gate thickness $c \leq 2.25a$, the increase in C_e above its corresponding value for the sharp-crested side sluice gate is $\leq$2.5%. Similarly, from (12*b*) and (14*b*), the increase in C_e above the corresponding value for the submerged sharp-crested sluice gate is $\leq$2.5% for $c \leq 0.78a$.

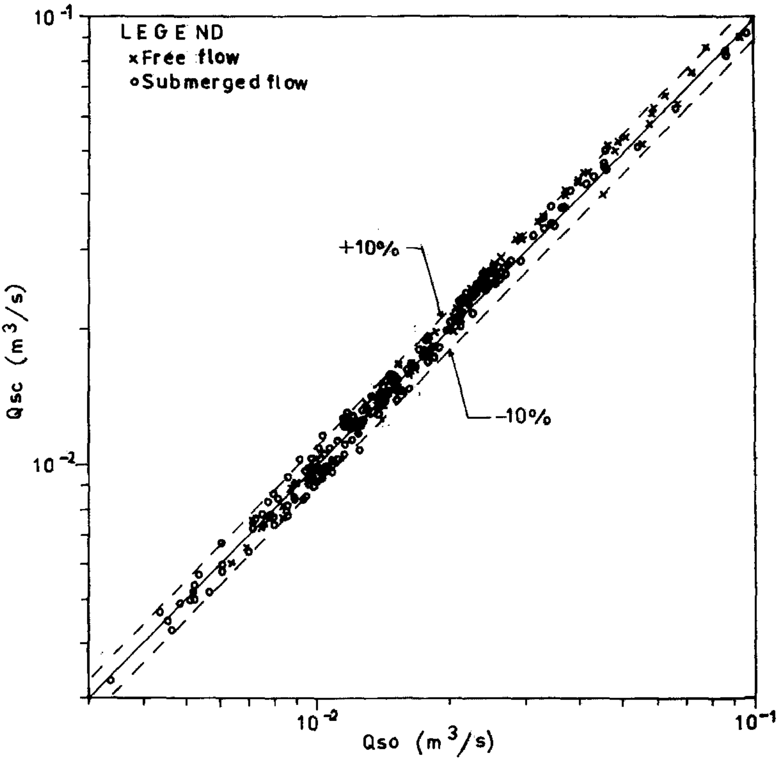

FIG. 4. Comparison of Observed and Computed Discharges (Sharp-Crested Side Sluice Gate)

Fig. 4 shows a comparison of Q_{so} and Q_{sc} for the data of the present study pertaining to sharp-crested side sluice gate. A perusal of Fig. 4 reveals that the majority of the data points lie in the error width of $\pm 10\%$. Similar results were obtained for broad-crested side sluice gate.

For the validation of (12*a*), Fig. 5 shows a comparison of computed and observed side-sluice-gate discharges using the data of Panda (1981). Data of Tanwar (1984) could not be included in Fig. 5, because the data of entrance depth y_0 for his experimental runs were not available—the measured water depth y at $x = b/2$ only. A perusal of Fig. 5 shows that the majority of the data points lie in the error width of $\pm 10\%$. Panda (1981) also reported a measured flow profile in the main channel. The flow profile was computed for his data using (3), (5), and (12*a*). A good agreement between the computed and measured profiles was observed.

SUBMERGENCE CRITERIA

It can be seen from (14*b*) that the elementary discharge coefficient is zero for $y = y_t$. An increase in y above y_t causes a rapid increase in C_e, until it equals the value of C_e predicted by (14*a*) for the free-flow condition. Thus y attains a maximum value y_{max}, given by

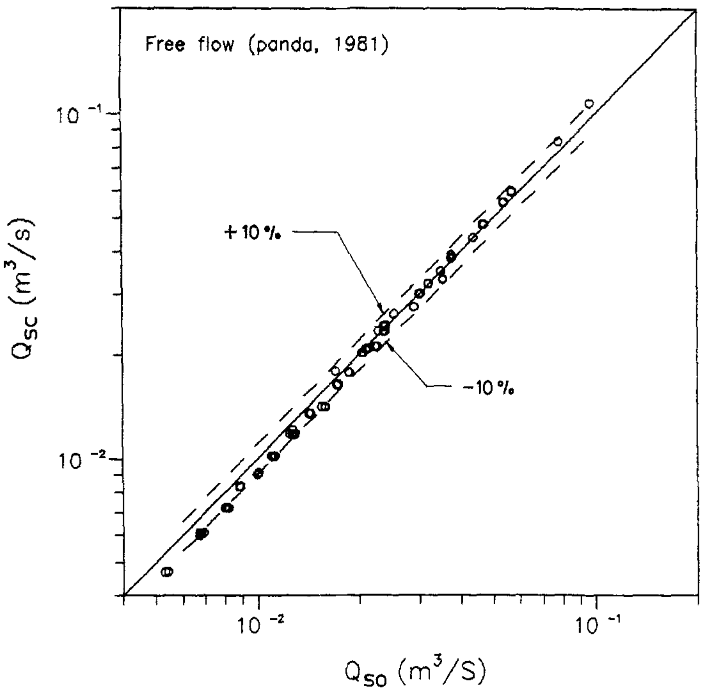

FIG. 5. Comparison of Observed and Computed Discharges (Sharp-Crested Side Sluice Gate)

$$y_{\max} = 2.5\left(1 + 0.0188\,\frac{c}{a}\right) y_t \left(\frac{y_t}{a}\right)^{0.2} \qquad (15)$$

at which the submerged-flow condition has just ended and the flow is free. Thus the condition for existence of submerged flow is given by the following. Broad-crested gate

$$y_t < y < 2.5\left(1 + 0.0188\,\frac{c}{a}\right) y_t \left(\frac{y_t}{a}\right)^{0.2} \qquad (16a)$$

Sharp-crested gate

$$y_t < y < 2.5 y_t \left(\frac{y_t}{a}\right)^{0.2} \qquad (16b)$$

Eqs. (16*a*) and (16*b*) are the applicability criteria for (14*b*) and (12*b*), respectively. Similarly, the conditions for the existence of free flow are as follows. Broad-crested gate

$$y \geq 2.5\left(1 + 0.0188\,\frac{c}{a}\right) y_t \left(\frac{y_t}{a}\right)^{0.2} \qquad (17a)$$

Sharp-crested gate

$$y \geq 2.5y_t\left(\frac{y_t}{a}\right)^{0.2} \qquad (17b)$$

CONCLUSION

Accurate equations for the elementary discharge coefficient for sharp- and broad-crested side sluice gates under free- and submerged-flow conditions were obtained. Using these equations, the discharge through the side sluice gate and the flow profile in the main channel in the region of the side sluice gate can be obtained by solving the spatially varied flow equation.

APPENDIX I. REFERENCES

Chow, V. T. (1959). *Open channel hydraulics.* McGraw-Hill Book Co., Inc., New York, N.Y.

Hager, W. H. (1983). "Hydraulics of distribution channels." *Proc., 20th Congress,* IAHR, Moscow, Soviet Union, 6, 534–541.

Hager, W. H., and Volkart, P. U. (1986). "Distribution channels." *J. Hydr. Engrg.,* ASCE, 112(10), 935–952.

Kindsvater, C. E., and Carter, R. W. (1957). "Discharge characteristics of thin plate weirs." *J. Hydr. Engrg. Div.,* ASCE, 83(6), 1453-1–1453-36.

Nougaro, J., Boyer, P., and Claria, J. (1975). "Location of diversion from a canal." *La Houille Blanche,* Paris, France, 30(4), 267–273 (in French).

Panda, S. (1981). "Characteristics of side sluice flow," ME thesis, University of Roorkee, Roorkee, India.

Swamee, P. K. (1992). "Sluice gate discharge equations." *J. Irrig. and Drain Engrg.,* ASCE, 118(1), 56–60.

Tanwar, M. P. S. (1984). "Flow through side sluice," ME thesis, University of Roorkee, Roorkee, India.

APPENDIX II. NOTATION

The following symbols are used in this paper:

A = flow area;
a = sluice gate opening;
B = channel width;
b = sluice gate length;
C_e = elementary discharge coefficient;
c = sluice gate lip width;
E = average percentage errors;
F_0 = Froude number at $x = 0$;
g = gravitational acceleration;
H = specific energy;
k_0–k_7 = constants;
N = number of experimental runs;
n = Manning's roughness coefficient;
Q = discharge;
Q_b = discharge at $x = b$;
Q_{sc} = side sluice discharge (computed);
Q_{so} = side sluice discharge (observed);
Q_0 = discharge at $x = 0$;

R = hydraulic radius;
S_f = friction slope;
S_0 = bed slope;
T = top width;
x = distance;
y = flow depth;
y_t = tailwater depth;
y_0 = flow depth at $x = 0$; and
ε = percentage error.

Subscripts

c = computed value;
i = index for a run; and
o = observed value.