JOURNAL OF CURRENT RESEARCH IN SCIENCE (ISSN 2322-5009)
CODEN (USA): JCRSDJ
2014, Vol. 2, No. 4, pp: 460-467
Available at www.jcrs010.com

ORIGINAL ARTICLE

NUMERICAL INVESTIGATION OF DISCHARGE COEFFICIENT IN COMBINED WEIR-GATE WITH EQUAL CONTRACTION

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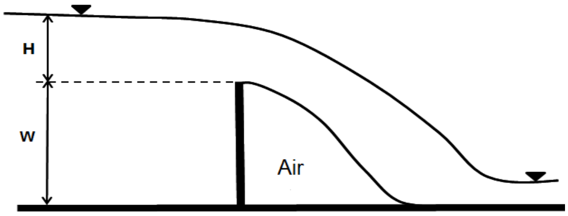
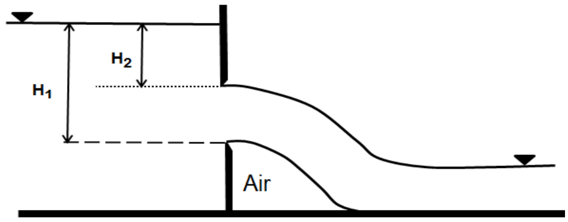
ABSTRACT: Researchers have always essayed to find methods that could increase discharge passing the measurement structures. Results of various experimental studies show that combining different measurement structures such as different kinds of weirs, flumes and gates increased discharge coefficient and lead to increasing of discharge passing from channel. One of the useful defined combined measurement structures is weir-gate that results in simultaneous passing the floats and sediments from the structure. In this research, Numerical simulation of combined sharp crest weir-gate was done using FLUENT software and the results of models compared with previous researches. The results show the defined combined weir-gate could increase the discharge coefficient effectively that result in increasing the flow discharge passing the structure. It was concluded that discharge coefficient of the structure reached to 0.66 in different conditions.
KEYWORDS: Weir, Gate, Combined structure, FLUENT software.

INTRODUCTION

Weirs and gates are extensively used for flow control and discharge measurement in open channels. These are obstruction structures generally put normal to the direction of flow. Flow discharge can be determined simply by recording the water depth upstream of the measurement structure. Weirs and gates may be combined together in one structure resulted a simultaneous flow over the weir and below the gate. Based on Negam *et al.,* (1997) results, a triangular above a rectangular opening is more efficient than reversed. The combined weir-gate is a relatively new structure suggested by several researchers. In figure 1, the shame of flow over weirs and below gates is given. The main advantage of the combined structure is the increasing of flow discharge passing through the system. Many studies have been conducted for different type of weirs and gates to find the relation between the water depth and the discharge passing through the structure (Aydin *et al.,* 2011).



a) Weir



b) Gate

Figure 1: Flow over rectangular sharp crest weir (a) and under a rectangular gate (b)

Based on the independent variables affecting the discharge flowing over weir and applying dimensional analysis, flow discharge coefficient as a function of dimensionless parameters can be obtained as:

$$C_d = f\left(\frac{H}{w}, \frac{b}{B}, \frac{H}{b}, R_e, W_e\right) \quad (1)$$

Where R_e and W_e are the Reynolds and Weber numbers respectively, H is the water depth upstream of the structure, w is the height of the weir, b is the width of the openings of the weir, B is the channel width.

Numerous researchers have done investigations on sharp crested weir hydraulic. Rehbock, (1929) purposed the flowing equation based on experimental data for estimating discharge coefficient of rectangular weir with wide equal to channel.

$$C_d = 0.611 + 0.08\left(\frac{H}{w}\right) \quad (2)$$

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In the equation, surface tension and viscosity force are neglect and it be only used in $\frac{H}{w} < 5$.

Kindsvater and Carter, (1957) introduced concepts of the effective weir width (b_e) and the effective head over the weir (h_e) that represent the combined effects of surface tension and viscosity on discharge coefficient. The results showed that head over the weir and the discharge coefficient are also effected by inside construction of water flow. Kindsvater and Carter, (1957) defined $b_e=b+K_b$ where K_b is a function of b/B and $h_e=h+K_h$ where K_h has a constant value of 0.001m and $C_{de}=k_1+k_2\ (\frac{H}{w})$.

Kandaswamy and Rouse, (1957) suggested discharge coefficient in $\frac{H}{w} > 15$ as following:

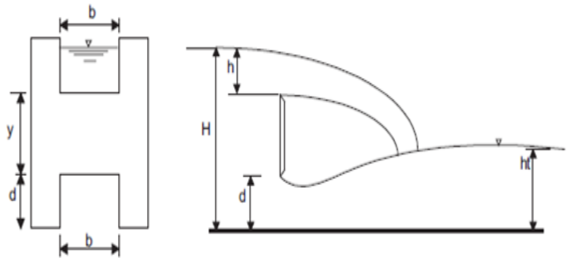
$$C_d = 1.06\ (1 + \frac{H}{w})^{1.5} \qquad (3)$$

Bos, (1989) demonstrated that the minimum water depth upstream of the structure must be equal 20 mm to having completely the characteristics of sharp crest weir. This limitation reduces the effects of viscosity and surface detention, so that Re and We is removed.

Initial researches on gate hydraulic have been done by Henry, (1950). Lately, Ferro, (2000) and Negam *et al.*, (2002) focused on it. Rajaratnam and Subramania, (1976) have done many researches about gates. Swamee, (1993) and Montes, (1997) provided equations for calculating discharge passing under gate. Swamee, (1993) developed a discharge equation based on Henry's experimental data. Montes, (1997) described a numerical method to solve Laplace equation of discharge flow of gate.

There have been several studies made for the combined weir and gate structure. Also some of the researches are experimental whereas others are numerical. Comprehensive studies dealing the simultaneous flow over weirs and below gates can be found in Negm *et al.*, (1994); Negm *et al.*, (1997) and Negm *et al.*, (2002). Negam and coworkers investigated the characteristics of simultaneous flow over weirs and below inverted V-Notches gate and a combined flow over weirs and below submerged gates. They demonstrated that using of common flow rate coefficient for these types of the combined weir-gate can produce large error. They suggested an equation for 90 degree V-Notches gate.

The characteristics of the combined weir-gate with equal contractions (Figure 2) were discussed by Negm *et al.*, (2002). They found that the flow parameters H/d and geometrical parameter, y/d, have major effects on the discharge while the other parameters are insignificant.



a) Cross section b) Longitudinal section

Figure 2: Simultaneous flow over weir and under gate with equal contractions (Negm *et al.*, 2002)

In the above Figure, h is effective water head upstream of weir, H is total water depth upstream of weir-gate, b is the width of the openings of the weir and gate, d is the height of the opening of the gate and y is the vertical distance between the bottom of the weir and top of the gate and h_t is water depth downstream of weir-gate.

Ferro, (2000) established experimentally the relation between stage and discharge for simultaneous flow over and under a sluice or a broad-crested gate. A theoretical analysis and an experimental investigation were coupled to find the stage–discharge relationship. Razavian and Heydarpour, (2007) studied on combined flow characteristics over rectangular weir - gate with unequal contractions (Figure 3). They presented that discharge coefficient was increasing with increasing of flow discharge and water head in upstream of the combined structure. Altan-Sakarya and Kokpinar, (2013) predicted discharge through H-weirs using optimization method and the method developed by Ferro, (2000).

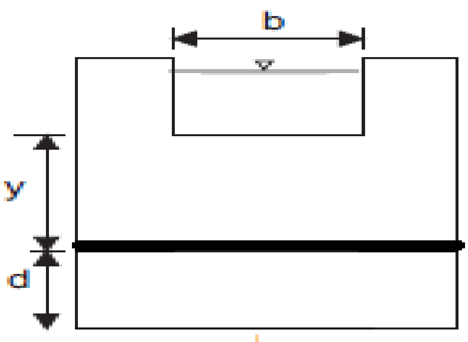


Figure 3: Cross section of combined weir-gate gate with unequal contractions

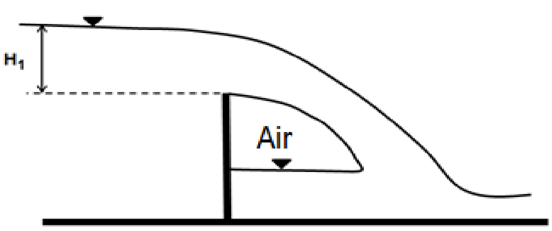
Overall, it has been concluded that mainly the gate section is passing water in lower flow. But in the higher flow, the combined weir - gate together are passing the flow and therefore water discharge can be increased. The main idea of this study is to depict numerically the discharge flowing through defined combined structure, where water flows simultaneously over and below the measuring structure.

In this study, the combined rectangular weir-gate in a rectangular cannel is simulated with FLUENT software. The result of simulated models are compared with experimental data of rectangular sharp-crested weir and the variations of flow discharge with respect to water depth are presented for both rectangular weir and combined weir-gate. Also, the discharge coefficients of previous researches are also compared with new developed coefficient.

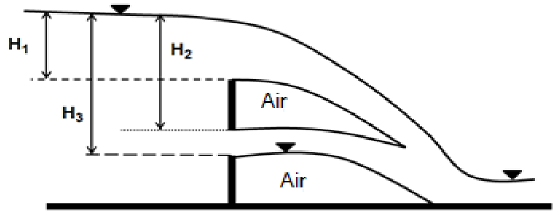
There are limited numbers of numerical studies made for simultaneous flow over and below the combined weir-gate in literature. But CFD simulation especially modeling with FLUENT software has been used in simulation of various hydraulic structures. These simulations show sufficient results with compared to experimental data. Some examples are such as modeling of flow pattern over cylindrical weir (Esmaii *et al.,* 2011), simulation of water hammer (Nikpour *et al.,* 2010) and numerical modeling of velocity and pressure distribution over broad crest weir (Rostami and Namaii, 2010). A study by Rostami and Namaii, (2010) shows that simulation results with FLUENT software has good agreement with experimental data. K- ε Realizable turbulence model has less error than the other turbulence models.

MATERIALS AND METHODS

In this research the flow discharge in the defined combined weir-gate was 2D simulated using FLUENT software and compared with experimental data. Flow discharge was numerically and experimentally investigated in the two type structures including single sharp crest weir and combined weir-gate. The Sketch of Longitudinal section of single weir and defined combined structure used in simulation is shown in Figure 4.



a) Single weir



b) Defined combined structure

Figure 4: Longitudinal section of single weir and the defined combined structure

Experiments used in performing the CFD model have been performed in a rectangular flume constructed at Hydraulics Laboratory of University of Tabriz, Iran. The flume with Plexiglas side wall was 10 m long and 0.25 m width. Also, the bed slope was 0.0022 and 0.5 deep. Water flow was supplied from circulating system and flow measurement was made by using pre-calibrated sharp-crested weir.

In the experiments, a sharp-crested weir with 0.25 height was put normal to the direction of flow. Water depth over weir (H_1) was varied between 2.9 – 12.7 cm and flow discharge was measured in all experiments. Summarized experimental data are shown in table 1. It is mentioned that length of weir and width of gate is equal to width of channel.

2.1. Numerical Model Description

FLUENT is one of the CFD models solving complex flow ranging from incompressible to highly compressible flows. Providing multiple choices of solver option, combined with a convergence-enhancing multi-grid method, *FLUENT* delivers optimum solution efficiency and accuracy for a wide range of speed regimes. *FLUENT* solves the governing 2D or 3D equations sequentially using the control volume method.

2.2. Governing equations

The governing equations of fluid flow in rivers and channels are generally based Reynolds averaged equations for incompressible free surface unsteady turbulent flows. In this study, it is assumed that the density of water is constant through the computational domain. The governing differential equations of mass and momentum balance for unsteady free surface flow can be expressed as (Chen *et al.,* 2002):

$$\rho\frac{\partial}{\partial x_i}(u_i uj) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_i \qquad (4)$$

$$\frac{\partial u_i}{\partial x_i} = 0 \qquad (5)$$

$$\tau_{ij} = \left[\rho(\upsilon+\upsilon_t)\left(\frac{\partial u_i}{\partial xi} + \frac{\partial uj}{\partial x_i}\right)\right] - \left[\frac{2}{3}\rho(k+\upsilon_t)\frac{\partial u_i}{\partial xi}\delta_{ij}\right] \qquad (6)$$

Where u_i and u_j is the velocity in the x_i and x_j direction; P is the total pressure; ν is the molecular viscosity, υ_t is the turbulence viscosity, g_i is the gravitational acceleration in the xi direction, τ_{ij} is shear stress tensor, ρ is the density of flow, K is turbulence kinetic energy, δ_{ij} is kronecker's delta. Turbulent flows can be simulated in *FLUENT* using different turbulent models such as standard K-ε, LES, RNG, or Reynolds-stress (RSM) closure schemes. The model optimizes computational efficiency by allowing the user to choose between various spatial (Second-order upwind, third-order, QUICK) discritization scheme.

The simplest and most widely used two-equation turbulence model is the k-ε model that solves two separate equations to allow the turbulent kinetic energy and dissipation rate to be independently determined. Control volume method (VOF) is one of the accurate methods to determine free surface level. This method is used to present surface level that is joined between two or several unmixed fluid. In this study, the control volume method was used for simulating multi-phase flow and k-ε turbulence model was selected to modeling turbulence flow.

2.3. Performed Steps in FLUENT software

At first, 2D geometry model of the combined structure was created in Gambit software and proper grid of model was produced. It is important to establish a grid structure that grid-independent results be obtained. Also, the grid structure must be fine enough. It was found that results are independent of grid size, if at least 3000 nodes are used in 2D simulating. Figure 5 represents the grid structure of the simulated combined structure. Then in Fluent software, appropriate boundary conditions are specified at the domain. Finally the model is run by using the control volume method and selecting the turbulence model and other specifications.

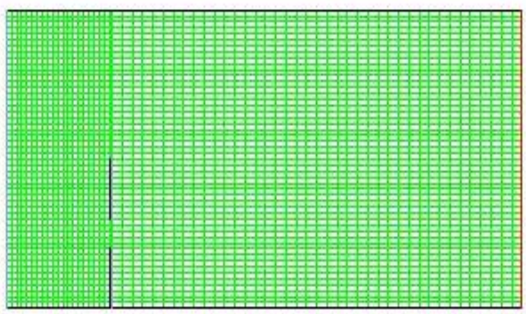


Figure 5: Model of combined weir-gate and its grid structure in Gambit software

Geometry characteristics of three simulated models are given in table 2. Gate opening is equal 5%, 10% and 20 of head over the weir. Also, Details of flow passing the combined structure are shown in figure 6. Design of the combined weir-gate has special condition that height structure over and under gate is equal; other hand gate location was in middle of the structure.

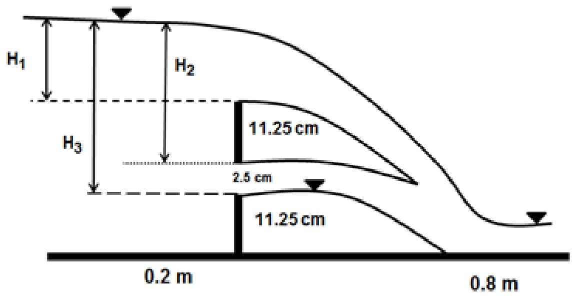


Figure 6: Details of flow passing the combined weir-gate with 10 % gate opening.

To compute the discharge of the combined weir-gate, the following equation may be obtained by adding the discharge over the weir and gate as:

$$Q = C_d[\, Q_w + Q_G \,] \quad (7)$$

Where Q is total actual discharge, Q_w is discharge over the weir, Q_G is discharge under the gate, C_d is coefficient of discharge. The discharge over the sharp crest weir (Q_w) can be calculated using the following equation (Aydin *et al.*, 2011):

$$Q_w = \frac{2}{3} C_{d_w} \sqrt{2g}\, b\, H_1^{\frac{3}{2}} \quad (8)$$

Where Q discharge over the weir, H_1 is the water head on the weir, C_{dw} is the discharge coefficient of the weir, b is the width of weir and g is the gravitational acceleration.

The discharge under the gate is calculated using the following equation adopted by Rajaratnam and Subramanya, (1967):

$$Q_G = \frac{2}{3} C_{d_G} \sqrt{2g}\; b\, (H_3^{\frac{3}{2}} - H_2^{\frac{3}{2}}) \quad (9)$$

Where Q_G is discharge under the gate, C_{dG} is the discharge coefficient of the gate, b is the width of gate, H_3 is the upstream water depth from bottom the gate and H_2 is the depth of water just top of the gate. Flow discharge equation of the combined weir-gate could be determined by replacing equations 8 and 9 in equation 7 as:

$$Q = \frac{2}{3} C_{d_w} \sqrt{2g}\, b\, H_1^{\frac{3}{2}} + \frac{2}{3} C_{d_G} \sqrt{2g}\, b \left(H_3^{\frac{3}{2}} - H_2^{\frac{3}{2}} \right) \quad (10)$$

Above equation could be simplified as:

$$Q = C_d \frac{2}{3} \sqrt{2g}\, b \left[H_1^{\frac{3}{2}} + H_3^{\frac{3}{2}} - H_2^{\frac{3}{2}} \right] \quad (11)$$

In this research, Equation 11 is used to calculate discharge coefficient of the combined structure and compared with Kindsvater -Carter and Rehbock's equation.

RESULTS AND DISCUSSION

By using experimental data (single sharp crest weir), discharge coefficients are determined for Rehbock and Kindezter –kater's equations and compared with equation 11 (table 3). Based on the results, Variation of Discharge coefficient values versus h/p are shown in figure 7. As shown in this Figure, the mentioned equations have approximately same result and error values are negligible.

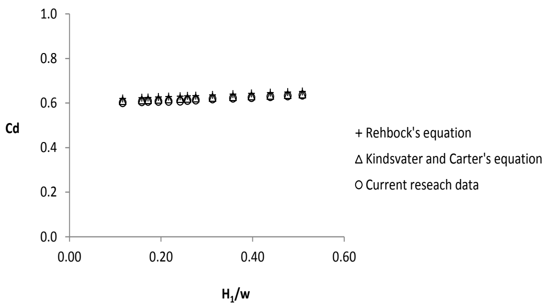


Figure 7: Variation of Discharge coefficient values versus $\frac{H_1}{w}$ for single weir

Figure 8 shows the simulated combined weir-gate that water flows through the structure. Results of the simulated models were collected and compared with experimental data (single weir). Numerical results obtained for the simulated models and experimental data (single weir) are given in table 4. In this table, H_t is upstream water depth in channel and q is flow discharge divided by channel width.

Figure 8: Simulated flow passing over and under the combined weir-gate

Results of the numerical models and experimental data as variation of discharge versus H_t in different structures are shown in figure 9. The results show that the flow discharge has increased in the combined structures. Otherwise, the combined weir-gate could increase discharge coefficient. It is also seen in constant upstream water head (H_t) that flow discharge increase as gate opening is equal 20 % of total weir height.

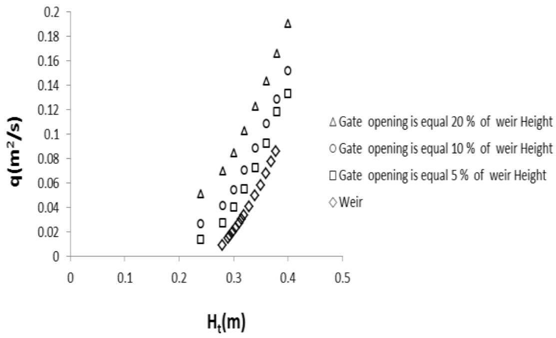


Figure 9: Variation of discharge versus H_t in studied models

Figure 10 shows variation of discharge coefficient versus $\frac{H_t}{w}$ for three simulated combined weir-gate and single weir. As shown in this Figure, discharge coefficient was increased efficiently by using the combined structure. Also, with increasing $\frac{H_t}{w}$, discharge coefficient value is reached to 0.66 in different structures.

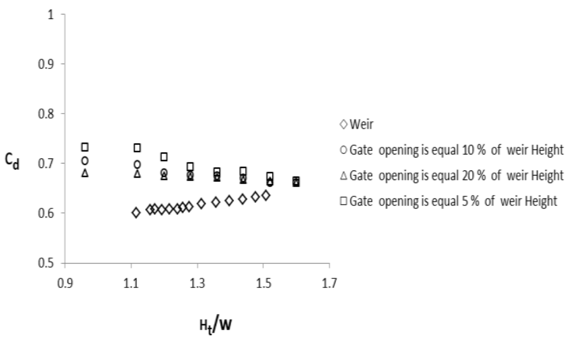


Figure 10: Variation of discharge coefficient versus $\frac{H_t}{w}$ in studied models

Also, results of this research were compared with the previous research results in table 5. The variation of discharge coefficient in the combined weir-gate is more than the other contracted or no contracted combined weir-gate (Negam *et al.*, 2002; Razavian and Heydarpour, 2007). This advantage is considerable in the combined weir-gate in comparison of contracted rectangular weir combined with no contracted gate.

CONCLUSIONS

In the present research, numerical simulation of the defined combined weir-gate was done and compared with previous studies. Summarized results are listed below:

1- The defined combined weir-gate caused increasing flow discharge passing the structure and therefore increased discharge coefficient.
2- Because of increasing flow discharge passing the structure, application of this structure is economic in small canal.
3- With increasing $\frac{H_t}{w}$ in single weir and the combined weir-gate, the discharge coefficient reached to constant value of 0.66.
4- In a constant water head, flow discharge reaches to maximum value in a way that height of gate opening increases. Otherwise, as height of gate opening increases more, combined flow passing over and under the structure increases.
5- It should be considered if height of gate opening increases extremely, pressure force of water could be damage the structure in high water depth.

REFERENCES

Altan-Sakarya B, Kokpinar MA. Computation of discharge for simultaneous flow over weirs and below gates (H-weirs). Flow Measurement and Instrumentation 2013; 29: 2–38.

Aydin I, Altan-Sakarya AB, Sisman C. Discharge formula for rectangular sharp-crested weirs. Flow Measurement and Instrumentation 2011; 22(2): 144-151.

Bos MG. Discharge measurement structures. International Institute for Land Reclamation and Improvement Washington the Netherlands 1989; Pub.No:20.

Chen Q, Dai G, Liu H. Volume of fluid for turbulence numerical simulation of stepped spillway over flow. Journal of Hydraulic Engineering 2002; 128(7): 683-688.

Esmaii K, Naghavi B, Kourosh Vahid F, Yazdi G. Numerical and experimental modeling of flow pattern over cylindrical weir. Journal of water and soil 2011; 24(1): 166-179.

Ferro V. Simultaneous Flow over and Under a Gate. Journal of Irrigation and Drainage Engineering 2000; 126(3): 190-193.

Gharahgezlou M, Masoudian M, Haber B, Salehi Neyshaboury SA. Laboratory investigation of combination of cylindrical and semi cylindrical weir-gate model in a small canal. Journal of water and soil conservation 2013; 20(1): 185-198 (In Persian).

Henry HR. Discussion to Diffusion of submerged jets. By Albertson ML, Dai YB, Jensen RA, Rouse H. Trans. ASCE 1950; 115: 687-694.

Kindsvater CE, Carter RW. Discharge Characteristics of Rectangular Thin Plate Weirs. Hydraulic Division Proc ASCE 1957; 83(6): 1-36.

Kandaswamy PK, Rouse H. Characteristics of flow over terminal weirs and sills. Journal of Hydraulics Division ASCE 1957; 83 (4):1-13.

Montes JS. Irrotational Flow and Real Fluid Effect under Planer Sluice Gate. Journal of Hydraulic Engineering 1997; 123(3): 219-232.

Negm AM, El-Saiad AA, Alhamid AA, Husain D. Characteristics of simultaneous flow over Weirs and below inverted V-Notches Gate. Civil Eng Research Magazine (CERM). Civil Eng Department. Faculty of Eng. Al-Azhar University Cairo. Egypt 1994; 16(9): 786-799.

Negm AM, El-Saiad AA, Saleh OK. Characteristics of combined flow over Weirs and below submerged Gates. Proc of Al-Mansoura Eng. 2nd Int Conf. (MEIC'97). 1-3 April. Faculty of Engineering. Al-Mansoura University. Al-Mansoura. Egypt 1997; III-B: 259-272.

Negm A, AL-Brahim M, AL-Hamid AA. Combined free flow over weir and below gates. Journal of Hydraulic Research 2002; 40(3):359-365.

Nikpour M, Hoseinzadeh Dalir A, Nazemi AH, Salmasi F. Flow simulation of water hammer by using Fluent software. 9th Iran hydraulic conference. University of Tarbiayt Modares. Tehran. Iran. 2010; pp:1-9 (In Persian).

Razavian SH, Heydarpour M. Investigation of discharge coefficient in sharp –crested Weir-Gate Models. 6th Iranian Conference of Hydraulic. University of ShahreKord. Iran. 2007; pp:1-12 (In Persian).

Rajaratnam N, Subramaniya K. Flow Equation for Sluice Gates. Journal of Irrigation and Drainage Division Proc ASCE 1967; 93(3): 167-186.

Rehbock T. Discussion of 'Precise Measurements. By Turner KB. Trans ASCE 1929; 93: 1143-1162.

Rostami M, Namaii M. Numerical simulation of velocity and pressure distribution over broad crest weir. 9th Iran hydraulic conference, University of Tarbiayt Modares, Tehran, Iran. 2010; pp:1-8 (In Persian).

Swamee PK. Critical Depth Equation for Irrigation Canals. Journal of Irrigation and Drainage Engineering ASCE 1993; 119 (2): 400-409.

Table 1: Experimental data

Number	H_1(cm)	Cd	Q (L/S)
1	2.90	0.601	2.30
2	3.95	0.606	3.63
3	4.29	0.608	4.11
4	4.85	0.607	4.92
5	5.41	0.608	5.78
6	6.03	0.608	6.79
5	6.43	0.612	7.51
6	6.89	0.614	8.34
7	7.80	0.618	10.10
8	8.91	0.622	12.38
9	9.92	0.625	14.57
10	10.95	0.629	16.98
11	11.90	0.632	19.32
12	12.70	0.635	21.40

Table 2: Geometry characteristics of studied models

No.	Type of structure	Height of weir (cm)	Gate opening (cm)	height structure over and under gate (cm)	Description
1	Single weir	25	-	-	-
2	Weir-gate	25	1.25	11.875	Gate opening is equal 5% of weir height
3	Weir-gate	25	2.5	11.25	Gate opening is equal 10% of weir height
4	Weir-gate	25	5	10	Gate opening is equal 20% of weir height

Table 3: Values of calculated discharge coefficient for single weir (experimental data)

Calculated Cd using equation 11	Calculated Cd using Rehbock's equation	Calculated Cd using Kindsvater –Carter's equation
0.601	0.620299	0.610717
0.606	0.623665	0.613874
0.608	0.624756	0.614896
0.607	0.626551	0.616579
0.608	0.628347	0.618263
0.608	0.630335	0.620126
0.612	0.631617	0.621329
0.614	0.633092	0.622711
0.618	0.63601	0.625447
0.622	0.639569	0.628784
0.625	0.642808	0.63182
0.629	0.64611	0.634916
0.632	0.649156	0.637772
0.635	0.651721	0.640176
Error percentage	6.7 %	1.29 %

Table 4: Experimental data (single weir) and Results of the simulated models

Results of experimental data (single weir)		Results of the simulated models (weir-gate)					
		gate opening is equal 5 % of weir height		gate opening is equal 10 % of weir height		gate opening is equal 20 % of weir height	
H_t (cm)	$q\ (\frac{lit/s}{m})$	H_t (cm)	$q\ (\frac{lit/s}{m})$	H_t (cm)	$q\ (\frac{lit/s}{m})$	H_t (cm)	$q\ (\frac{lit/s}{m})$
37.7	85.6	40	133.1	40	151.81	40	190.4
36.9	77.28						
35.95	67.92	38	117.9	38	128.50	38	166.05
34.92	58.28						
33.91	49.52	36	92	36	108.3	36	143.54
32.8	40.4	34	72	34	88.47	34	122.60
31.89	33.36	32	54.89	32	70.03	32	102.69
31.43	30.04						
31.03	27.16	30	40.01	30	54	30	84.77
30.41	23.12						
29.85	19.68	28	27.16	28	41.15	28	69.9
29.29	16.44						
28.95	14.52	24	13.74	24	26.47	24	51
27.9	9.2						

Table 5: Comparison of discharge coefficient values in various researches

Researcher	Type of structure	discharge coefficient values	Flow condition
Negam et.al (2002)	Rectangular weir- gate with contracted	0.51 <C_d<0.68	$0.47 < \frac{y}{d} < 4$ $2.5 < \frac{H_t}{d} < 7.6$ $0.65 < \frac{b}{d} < 5$
Gharahgezlou et al (2013)	Cylindrical weir- gate and semi cylindrical weir- gate	0.38 <C_d<0.96	$5.5 < \frac{H_t}{d} < 13$
Razaviyan and Heydarpour (2007)	Contracted rectangular weir combined with no contracted gate	0.55 <C_d<0.61	$3 < \frac{H_t}{d} < 7$ $2 < \frac{b}{d} < 4.5$ $1.5 < \frac{y}{d} < 2.7$
Current research	The combined weir-gate with no contracted	$C_d \approx 0.66$	Gate opening is equal 5, 10 and 20 % of weir height, $\frac{H_t}{w} > 1.44$