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ANALYSIS OF SUBMERGED FLOW UNDER A GATE WITH PRISMATIC SILL

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ABSTRACT

Sluice gates are widely used in irrigation structure, sills under gates has positive effect on flow performance under the gate and reduce its height. An experimental study in a laboratory flume is carried out to study submerged flow passing the opening between the sill and the gate. Four different heights of trapezoidal sill models were used and one without sill, the five groups were ran with four different gate opening. The basic principles of statistical analysis are employed to correlate between the hydraulic and geometric dimensionless parameters with the discharge coefficient. Different relationship models with acceptable significance are suggested. It was found that the some of dimensionless parameters effecting positively on the value of discharge coefficient by increasing its value such as (d/B, Fr, P/Y1, P/d), and other decreasing the value of C_d such as (Y_t/d, P/B, H/d, Y_1/Y_2, P/Y_2, P/H). The value of C_d ranges from 0.34 to 0.77, with Standard Error 0.006411. Within the limitations of the present experimental work an equation for prediction the value of the discharge coefficient is suggested with R square is 0.936 and stadard Error of estimate equle to 0.0240235. The actual discharge was checked by the sugested equation which shows a good greement with Adj. R^2=0.993.

Keywords: prismatic sill, sluice gate, gate opening, coefficient of discharge, height of sill.

INTRODUCTION

Discharge through the irrigation canals is commonly controlled by means of gates. Gates may be free or submerged according to the extent of the water depth downstream the gate relative to the gate opening. Sills reduce the height of the gates and consequently the pressure forces acting on it, then the height decrease the weight of the gate, operation force and cost. Sills are also effective in dissipating the energy below gates. Many studies have been made to study free and submerged flow discharged through the sluice gate without sill. Masliyah *et al*., (1985), Finni and Jeppson, (1991) studied the characteristics of flow under vertical sluice gate theoretically using numerical and finite elements methods. Jung-Fu Yen *et al*. (2001) and M. Bijankhan *et al*. (2012) investigated the flow movement through a sluice gate for both free and submerged flow conditions experimentally using laboratory channels. They developed stage-discharge relationship. H. Khalili Shayan, J. Farhoudi (2013), studied the energy loss of free flow under sluice gate; they present an equation for estimating energy loss factor and then the effect of this parameter on increasing discharge coefficient's accuracy.

Studies concerned the effect of sills on the free and submerged flow characteristics under sluice gates have been investigated also by many investigators. Salem (1990) studied the radial gate with sill of flat top and curved top with different heights under different flow conditions. It was found that the curved top sill increased the value of discharge coefficient C_d. Negm *et al*. (1993.a) investigated the effect of sill crest shape on the length of the free hydraulic jump and on the discharge coefficient C_d in the case of supercritical free flow conditions. Saad (2007) investigated the effect of circular-crested sill shapes under sluice gate on supercritical free flow characteristics. It was found that, the main factor which affects C_d value is the geometric shape of the sill. Saiad *et al*. (1991a) studied the effect of a sill under gate for submerged flow conditions using trapezoidal flat top sills with different downstream slopes and different heights, their study showed that C_d increases by increasing downstream slope of sill. Ibrahim (2000) analyzed the experimental data of supercritical submerged flows at fixed Froude number FG (1.806, 1.462, 1.255 and 1.018). He predict equation for the discharge coefficient C_d in terms of FG, gate opening G and the differential head on the gate ΔH. Ibrahim also conclude that the discharge coefficient attain their maximum values when the lateral sill is constructed at a distance of ¾ of the basin length from the gate. Negm (2000b) extended the study of Ibrahim by analyzing the experimental data of subcritical flow below gate in radial basin with sill; he used the same experimental configuration of Ibrahim and suggested an equation for estimating the discharge coefficient, which is nearly the same form of Ibrahim, but without the constant value in the nominator. Negm (2000a) compared the performance of rectangular and radial stilling basins on the discharge characteristics and hydraulic jump. It was concluded that the radial basin is more efficient regarding the whole characteristics.

Salama (1987) tested three models of sills with different downstream slopes and vertical upstream face. He found that the value of Cd under the gate is increased by constructing a sill.

Negm (1998) investigated the effect of the sill parameters (sill height to the sill top width Z/b and sill height to the sill bottom width Z/B) on flow below submerged gate, he found that the sill under the gate increases Cd of the gate and the rate of increase depends on the configuration of both the sill and the gate as well as on both the sill and flow parameters.

Negm, A.M. *et al*. (2001) studied the characteristics of submerged flow below vertical gate with sill upstream of horizontal diverging channel reach, they carried their experimental study in a canal of 10cm wide and 31 cm deep and 3m long. They noticed that the presence of sill under the gate has a remarkable effect on the discharge coefficient of the gate, and the observed variations (or scatter of data) in the discharge coefficients are depended on the under-gate Froude number and the differential head ratio.

The effect of the relative height of sill under gate with downstream slope of 1:5 was studied by, Negm, A. M. *et al*. (1993), and Negm, M. (1994). Neveen Y. Saad, (2011), investigated the effect of the circular-crested sills. The study is investigated in a flume with 250 cm long, 15 cm wide and 30 cm depth, the experimental study was carried for seven models of fixed slops upstream and downstream with a constant height. She has found that the main factor affects the discharge coefficient is B/Z (Z= sill height, B=bottom width of the sill), and the circular-crested sill produces a bigger discharge coefficient than the flat-crested sill only if B/Z of the circular-crested sill is equal or smaller than that of the flat-crested one.

The objective of the present study is to investigate the effect of different heights of prismatic sill, and different downstream and upstream slopes of the model, with multiple gate opening of vertical sluice gate on the equation of discharge coefficient in case of submerged flow condition.

THEORETICAL BACKGROUND

The flow under submerged sluice gate is as flow throw opening, the discharges capacity depends on the difference in depth between the upstream and downstream (H), which is the head that should over come all the resistance between the two sections, Equation (1) fixed the general parameters that effect theoretically the discharge, and Figure-1 shows the definition sketch for the flow with the geometric parameters. The actual discharge is affected by many physical properties which can be simulated in the coefficient of discharge (C_d) for the overall physical situation, as in equation (2).

$$Q_{th} = W \cdot d\sqrt{2gH} \qquad (1)$$

Where

Q_{th} = the theoretical discharge passing under gate (L^3 /T)
W = width of channel (L)
d = the gate opening (L)
H = difference in head (L)
g = gravitational acceleration (LT^{-2})

$$C_d = \frac{Q_{act}}{Q_{th}} \qquad (2)$$

Where
C_d = coefficient of discharge
Q_{act} = the actual discharge passing under gate (L^3 /T)

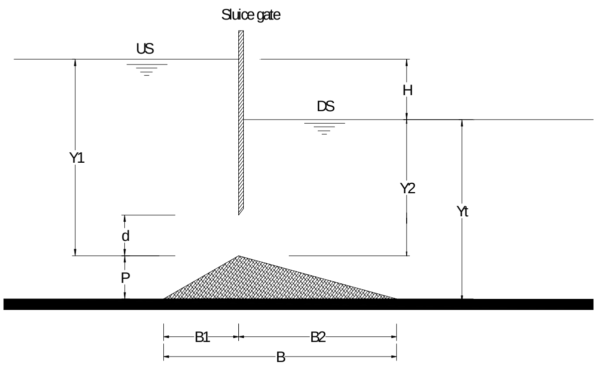


Figure-1. Definition sketch.

Prismatic sill with a total length (B) and four different heights (P) affects the performance of gate. Based on the above two equations and using dimensional analysis, the following functional relationship of dimensionless parameters can be obtained.

$$C_d = f(F_r, \frac{Y_1}{Y_2}, \frac{P}{H}, \frac{H}{d}, \frac{P}{B}, \frac{P}{d}, \frac{P}{Y_1}, \frac{P}{Y_2}, \frac{Y_t}{d}, \frac{d}{B}, R_e, W_e) \qquad (3)$$

Where

Y_1 = the depth of water over the sill upstream (L)
Y_2 = the depth of water over the sill downstream (L)
Y_t = the depth of tail water over the bed =Y_2+P (L)
B = the total length of sill (L)
P = height of sill (L)
F_r = Froud number under gate
R_e = Reynolds number
W_e = Weber Number

The values of Reynolds number and Weber number are not affected due to turbulent flow and neglecting surface tension. Froude number can be presented by the following relation.

$$F_r = \frac{Q_{act}}{W \cdot d\sqrt{gd}} \qquad (4)$$

EXPERIMENTAL WORK

The experimental investigation was carried out in a horizontal flume of working length 2.4m, having a rectangular cross section of 0.25m height and 0.075m width. Accurate point gauge with venier scale reading to $0.1* 10^{-3}$ m was used for measurements of flow depth at center line of flume. A sluice gate of 0.004 m thickness of plastic was used with regulating mechanism. The experiments carried out using 203 runs of discharges on five groups of sluice gate. Four models of prismatic sills were made of Mahogany wood with a total length B

=0.373 m, each model have different heights (P), Figure-2 shows photo for the models and the flow performance.

Figure-2. Representation of the sill models and sluice gate.

The models were classified into five groups depending on the value of sill height and the gate opening; Table-1 shows the groups.

Table-1. Details of the model tested.

Group	Model No.	Depth d (cm)	S1	S2	d/B	P/B
A P=0	1	1.5	-	-	0.04	0
	2	2	-	-	0.05	0
	3	2.5	-	-	0.08	0
	4	3	-	-	0.11	0
B P=2cm	5	1.5	0.22	0.07	0.04	0.05
	6	2	0.22	0.07	0.05	0.05
	7	2.5	0.22	0.07	0.08	0.05
	8	3	0.22	0.07	0.11	0.05
C P=3cm	9	1.5	0.33	0.11	0.04	0.08
	10	2	0.33	0.11	0.05	0.08
	11	2.5	0.33	0.11	0.08	0.08
	12	3	0.33	0.11	0.11	0.08
D P=4cm	13	1.5	0.44	0.14	0.04	0.11
	14	2	0.44	0.14	0.05	0.11
	15	2.5	0.44	0.14	0.08	0.11
	16	3	0.44	0.14	0.11	0.11
E P=5cm	17	1.5	0.55	0.18	0.04	0.13
	18	2	0.55	0.18	0.05	0.13
	19	2.5	0.55	0.18	008	0.13
	20	3	0.55	0.18	0.11	0.13

RESULTS and DISCUSSIONS

The data collected from the tests of the five groups (four sills and one without sill) models and four heights of gate opening are presented in Figure-3 for gate opening 0.02 m and five sill heights. It is clear that the discharge passing under the gate increases with increase of sill height within the experimental range. That is due to the gradually entrance to the gate opening and the gradually exit from the gate.

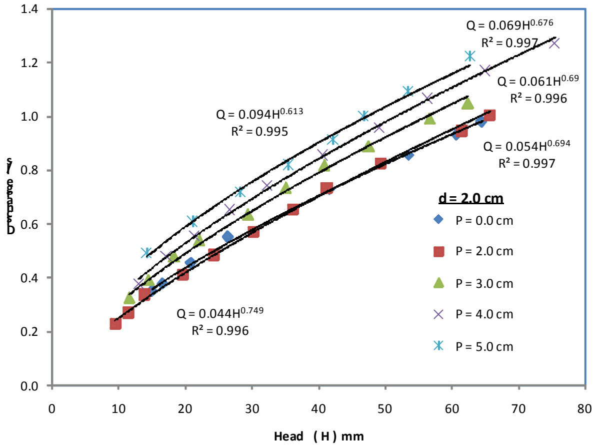
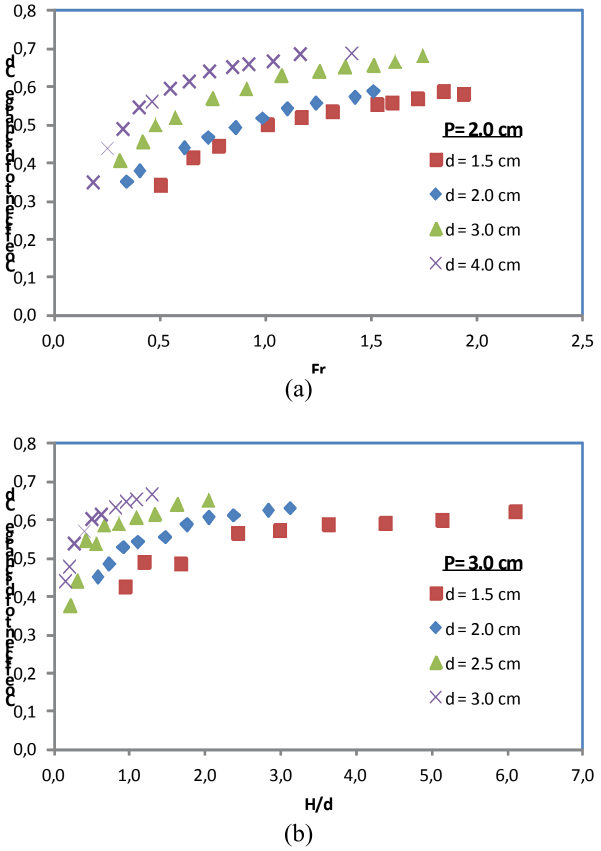


Figure-3. Relation between the discharge and head for d = 0.002 m.

The calculated value of discharge coefficient C_d in equation (2) was studied with the dimensionless parameters in equation (3). It is clear that the value of C_d increases with the increase of H for a fixed value of d and increases with the increase of gate opening, Figure-4 shows the relation.

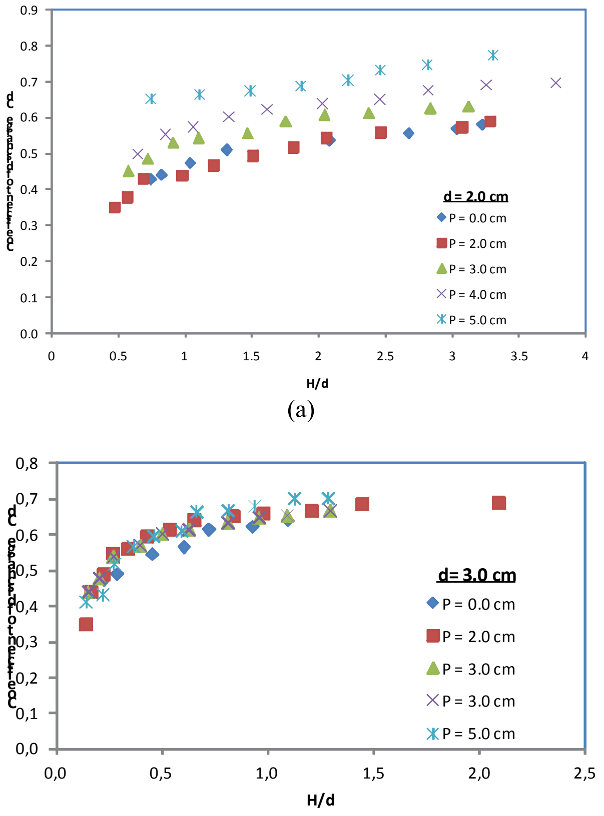


(a)

(b)

Figure-4. Relation between the discharge coefficient and H/d for different d.

The value of C_d increases with increase of H/d Figure-5 which shows the tendency of increasing with the increase of sill height with the experimental rate.



(a)

(b)

Figure-5. Relation between discharge coefficient and H/d for different P.

It also clear that the value of C_d increases with increases of Froude's number under the gate and the sill height as shown in Figure-6. The increases of C_d are due to increase of the velocity through the gate opening and the gradually decreasing value of the velocity after the gate due the slope of the sill downstream.

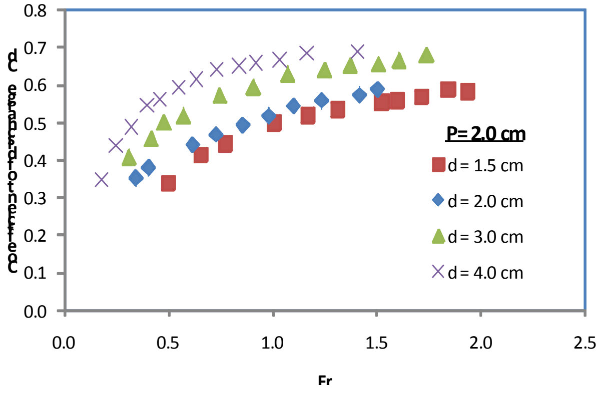
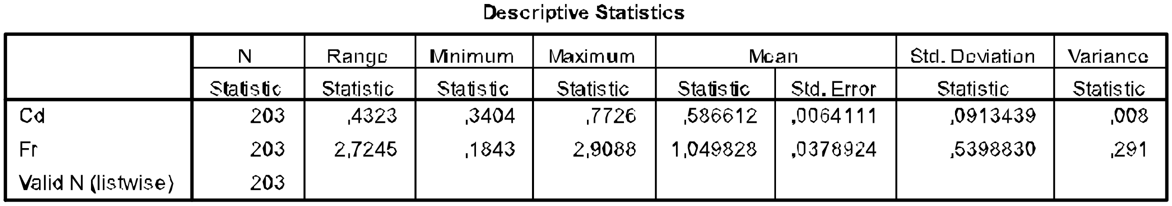


Figure-6. Relation between discharge coefficient and Fr for different d.

The descriptive analysis of the data,for C_d and Fr is shown in Table-2. The discharge coefficient C_d varies in the range from 0.7726 to 0.3404, with Standard Error 0.006411 and Standard Deviation 0.091344. To find the mathematical relation of the coefficient of discharge C_d with other dimensionless parameters, the total experimatal measures of five groups, four heights of gate openings and the calculated values of the dimensionless parameters of the equation (3) were combinrd to carry stastical analysis for the data by using the fasilites of the SPSS 17 Package. The correlation between the depentent variable C_d with the calculated dimiensionless parameters was studied, it was found that the indepentednt parametres (Fr, P/B, H/d, Y_1/Y_2, P/Y_2, P/d and P/H) have a significant correlation at the 0.01 level (2- tailed) while (Y_t/d) is significant at 0.05 level (2-tailed). The parameter (d/B) and (P/Y_1) shows that the significency is not noticiple with C_d, but it is heighly correlated with six other diemensionless parameters at 0.01 level (2-tailed)in the corelation matrix. The highest positve Pearson Correlation is factor 0.623 between the C_d and Fr.

Table-2. Descriptive analysis of the calculated coefficient of discharge and Fr.



Descriptive Statistics

	N	Range	Minimum	Maximum	Mean		Std. Deviation	Variance
	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error	Statistic	Statistic
Cd	203	,4323	,3404	,7726	,586612	,0064111	,0913439	,008
Fr	203	2,7245	,1843	2,9088	1,049828	,0378924	,5398830	,291
Valid N (listwise)	203							

Nonlinear Regression Analysis of 46 different models is carried on by the same package. The models were defined in three equation types, the linear, square and power. The best and simplest forms of equations were the linear form with and without constant. The worst equations were the multiplication of parameters with or without power. To show some best models from the linear with and without constant, and some of other forms, 10 models has been chosen as shown in Table-3 with the highest R^2.

Table-3. The regression models analysis.

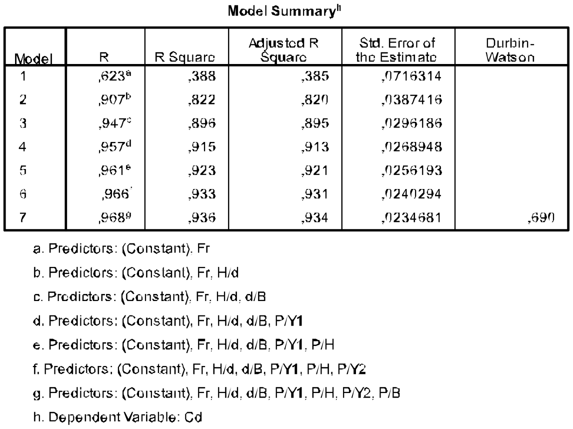
No.	**Equation**	$\mathbf{R^2}$
1	$Cd = 0.363 + 0.408Fr - 0.018\frac{Yt}{d} - 0.245\frac{P}{B} - 0.054\frac{H}{d} - 0.133\frac{Y1}{Y2} + 0.523\frac{P}{Y1} - 0.233\frac{P}{Y2} + 0.015\frac{P}{d} - 0.16\frac{P}{H} + 2.386\frac{d}{B}$	0.943
2	$Cd = 0.110 + 0.373Fr - 0.398\frac{P}{B} - 0.068\frac{H}{d} + 0.618\frac{P}{Y1} - 0.251\frac{P}{Y2} - 0.017\frac{P}{H} + 3.198\frac{d}{B}$	0.936
3	$Cd = 0.574Fr - 0.117\frac{Yt}{d} + 0.186\frac{P}{B} - 0.752\frac{H}{d} - 0.613\frac{Y1}{Y2} + 0.386\frac{P}{Y1} - 0.309\frac{P}{Y2} + 0.042\frac{P}{d} - 0.262\frac{d}{B}$	0.935
4	$Cd = 0.388Fr - 0.730\frac{P}{B} - 0.056\frac{H}{d} + 0.913\frac{P}{Y1} - 0.373\frac{P}{Y2} - 0.022\frac{P}{H} + 4.373\frac{d}{B}$	0,916
5	$Cd = 0.465Fr - 0.850\frac{P}{B} - 0.085\frac{H}{d} + 0.502\frac{P}{Y1} - 0.151\frac{P}{Y2} + 3.952\frac{d}{B}$	0.887
6	$Cd = -5.512 + Fr^{0.386} + (\frac{Yt}{d})^{-0.105} + (\frac{P}{B})^{3.045} + (\frac{H}{d})^{-0.031} + (\frac{Y_1}{Y_2})^{-0.356} + (\frac{P}{Y_1})^{10.946} + (\frac{P}{Y_2})^{12.150} + (\frac{P}{d}) + (\frac{P}{H})^{0..032} + (\frac{d}{B})^{0,341}$	0.924
7	$Cd = 0.319 + 0.129Fr^2 + 0.000(\frac{Yt}{d})^2 + 1.568(\frac{P}{B})^2 - 0.012(\frac{H}{d})^2 + 0.012(\frac{Y1}{Y2})^2 + 0.444(\frac{P}{Y1})^2 - 0.104(\frac{P}{Y2})^2 - 0.003(\frac{P}{d})^2$ $- 0.003(\frac{P}{H})^2 + 28.942(\frac{d}{B})^2$	0.854
8	$Cd = 0.340 + 0.127Fr^2 + 1.038(\frac{P}{B})^2 - 0.013(\frac{H}{d})^2 + 0.011(\frac{Y1}{Y2})^2 + 0.164(\frac{P}{Y1})^2 - 0.138(\frac{P}{Y2})^2 + 27.094(\frac{d}{B})^2$	0.78
9	$Cd = 0.069Fr^2 + 0.004(\frac{Yt}{d})^2 + 0.058(\frac{P}{B})^2 - 0.014(\frac{H}{d})^2 + 0.115(\frac{Y1}{Y2})^2 + 0.688(\frac{P}{Y1})^2 - 0.149(\frac{P}{Y2})^2 - 0.010(\frac{P}{d})^2$ $- 0.003(\frac{P}{H})^2 + 53.624(\frac{d}{B})^2$	0.782
10	$Cd = 0.504 + 0.115Fr^2 + 0.551\left(\frac{Y1}{Y2}\right)^2 - 0.011\left(\frac{H}{d}\right)^2 + 4.530\left(\frac{P}{B}\right)^2 - 0.002\left(\frac{P}{H}\right)^2 + 0.010\left(\frac{P}{d}\right)^2$	0.680

The first equation in the table include all the dimensionless paramters. Equation (3) has the highest R^2 equal to 0.944. while the second equation in the table is simplest than the first one for predecting the value of discharge coefficient C_d, it has been found by the regression of the data of C_d assusieted with 10 dimensionsless parameters using stepwise method of including independent varables in modele to determine statisticaly significnce pridictors in the equation by starting the modele with the higher indepent correlation varaible in the matrix at confidence level of 95% while after including seven indepentent varibles and stopped with R square is 0.936 and stadard Error of estimate equle to 0.0240235.

$$Cd = 0.110 + 0.373Fr - 0.398\frac{P}{B} - 0.068\frac{H}{d} + 0.618\frac{P}{Y1} - 0.251\frac{P}{Y2} - 0.017\frac{P}{H} + 3.198\frac{d}{B} \qquad (5)$$

The statistical analysis output details for the proposed equation (5) are shown in Table-4 and Table-5. The plot of the normal P-P regression standardized residual is shown on Figure-7.

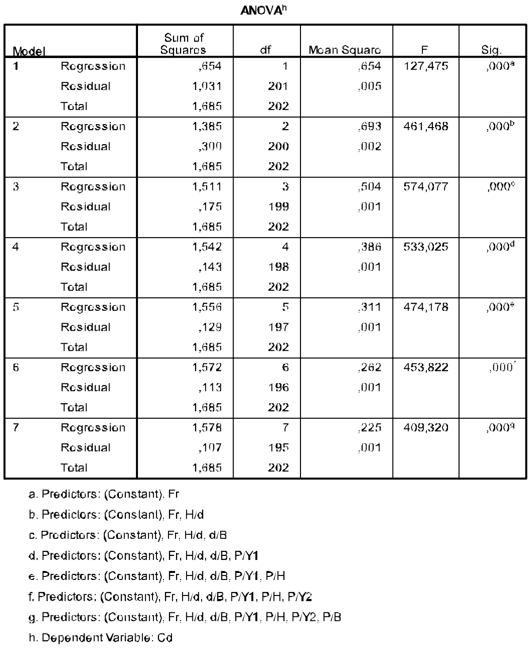
Table-4. Stepwise regression analysis.



Model Summary^{h}

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	,623^{a}	,388	,385	,0716314	
2	,907^{b}	,822	,820	,0387416	
3	,947^{c}	,896	,895	,0296186	
4	,957^{d}	,915	,913	,0268948	
5	,961^{e}	,923	,921	,0256193	
6	,966^{f}	,933	,931	,0240294	
7	,968^{g}	,936	,934	,0234681	,690

a. Predictors: (Constant), Fr
b. Predictors: (Constant), Fr, H/d
c. Predictors: (Constant), Fr, H/d, d/B
d. Predictors: (Constant), Fr, H/d, d/B, P/Y1
e. Predictors: (Constant), Fr, H/d, d/B, P/Y1, P/H
f. Predictors: (Constant), Fr, H/d, d/B, P/Y1, P/H, P/Y2
g. Predictors: (Constant), Fr, H/d, d/B, P/Y1, P/H, P/Y2, P/B
h. Dependent Variable: Cd

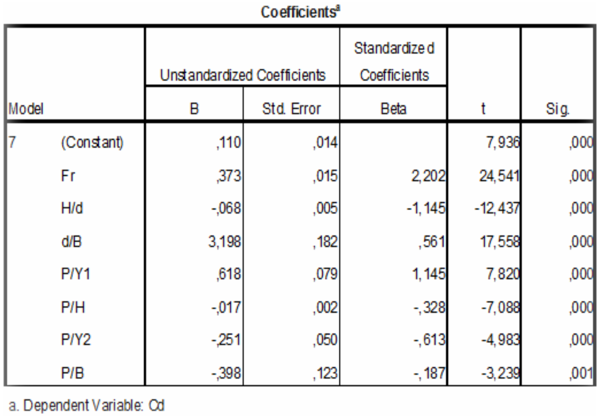


ANOVA^{h}

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	,654	1	,654	127,475	,000^{a}
	Residual	1,031	201	,005		
	Total	1,685	202			
2	Regression	1,385	2	,693	461,468	,000^{b}
	Residual	,300	200	,002		
	Total	1,685	202			
3	Regression	1,511	3	,504	574,077	,000^{c}
	Residual	,175	199	,001		
	Total	1,685	202			
4	Regression	1,542	4	,386	533,025	,000^{d}
	Residual	,143	198	,001		
	Total	1,685	202			
5	Regression	1,556	5	,311	474,178	,000^{e}
	Residual	,129	197	,001		
	Total	1,685	202			
6	Regression	1,572	6	,262	453,822	,000^{f}
	Residual	,113	196	,001		
	Total	1,685	202			
7	Regression	1,578	7	,225	409,320	,000^{g}
	Residual	,107	195	,001		
	Total	1,685	202			

a. Predictors: (Constant), Fr
b. Predictors: (Constant), Fr, H/d
c. Predictors: (Constant), Fr, H/d, d/B
d. Predictors: (Constant), Fr, H/d, d/B, P/Y1
e. Predictors: (Constant), Fr, H/d, d/B, P/Y1, P/H
f. Predictors: (Constant), Fr, H/d, d/B, P/Y1, P/H, P/Y2
g. Predictors: (Constant), Fr, H/d, d/B, P/Y1, P/H, P/Y2, P/B
h. Dependent Variable: Cd

Table-5. Stepwise regression coefficients.



Coefficients^{a}

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
7	(Constant)	,110	,014		7,936	,000
	Fr	,373	,015	2,202	24,541	,000
	H/d	-,068	,005	-1,145	-12,437	,000
	d/B	3,198	,182	,561	17,558	,000
	P/Y1	,618	,079	1,145	7,820	,000
	P/H	-,017	,002	-,328	-7,088	,000
	P/Y2	-,251	,050	-,613	-4,983	,000
	P/B	-,398	,123	-,187	-3,239	,001

a. Dependent Variable: Cd

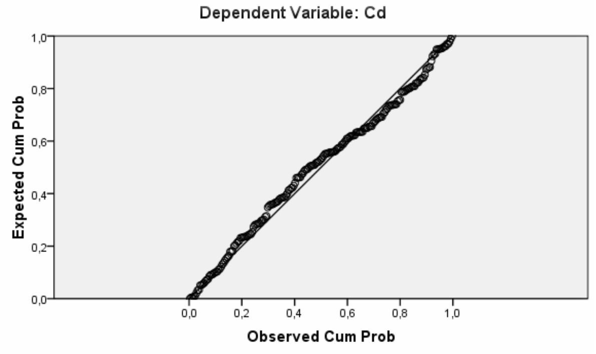
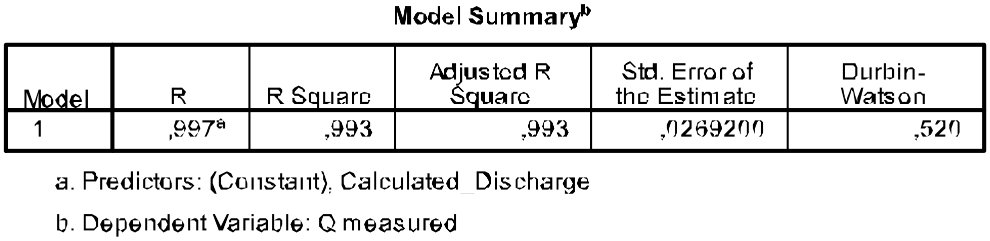


Figure-7. Normal P-P plot regression standardized residual.

Equation (5) for prediction of C_d is checked by calculating the value of discharge and then correlated with the measured discharge. It has a significant correlation at the 0.01 level (2- tailed) with Adj. R^2=0.993. The model summery and ANOVA tables which shows the relation of the regrresion between the actual (measured) discharge and the calculated value from Cd and theoretical discharge are shown in Tables 6 and 7. It is clear that the value of F-statistics is very high.

Table-6. Regression of linear model.



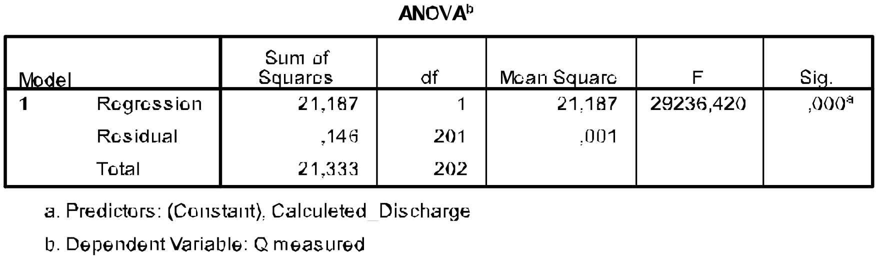
Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	,997[a]	,993	,993	,0269200	,520

a. Predictors: (Constant), Calculated_Discharge

b. Dependent Variable: Q measured

Table-7. The significance of the relation.



ANOVA[b]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	21,187	1	21,187	29236,420	,000[a]
	Residual	,146	201	,001		
	Total	21,333	202			

a. Predictors: (Constant), Calculeted_Discharge

b. Dependent Variable: Q measured

CONCLUSIONS

The performance of sluice gate with a sill was studied experimantaly in open channel by changeing the height of the sill. From statistical analysing of experimental data the following conclusions may fixed.

a) The prismatic sill under the gate has positive effect on the performance of the gate flow.
b) The value of C_d increases with the increase of d/B, Fr, P/Y1, P/d.
c) The value of C_d decreases with increases Y_t/d, P/B, H/d, Y_1/Y_2, P/Y_2, P/H.
d) The value of C_d range from 0.34 to 0.77, with Standard Error 0.006411
e) Within the limitations of the present experimental work a discharge prediction (Equation(5)) is developed with mean percent error of 0.026%.

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