## Research Article
## Surface Roughness Effects on Discharge Coefficient of Broad Crested Weir

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**Abstract:** The aim of this study is to investigate the effects of surface roughness sizes on the discharge coefficient for a broad crested weirs. For this purpose, three models having different lengths of broad crested weirs were tested in a horizontal flume. In each model, the surface was roughed four times. Experimental results of all models showed that the logical negative effect of roughness increased on the discharge (Q) for different values of length. The performance of broad crested weir improved with decrease ratio of roughness to the weir height (Ks/P) and with the increase of the total Head to the Length (H/L). An empirical equation was obtained to estimate the variation of discharge coefficient $C_d$ in terms total head to length ratio, with total head to roughness ratio.

**Keywords:** Broad crested weir, discharge coefficient, surface roughness, total head

### INTRODUCTION

One of the most important hydraulic structures which are used in irrigation systems and regulation of water depth in rivers, canals and other natural open channels are the broad crested weirs, which can be defined as a vertical barrier in a canal or tank side in which the water may flow freely. This weir can be used to measure the discharge and to raise the water level in the upstream. There are many researchers have been proposed some useful empirical discharge equations for these weirs. On one hand, the simple board crested weir has been studied by many researches such as Ramamurthy et al. (1988) gave a condition that the upstream corner of board crested weir is considered sharp if the radius of curvature at this corner is less than 9.4% of weir height. Hydraulic features of flow over square edge broad crested weirs with vertical upstream face were studied experimentally by Hager and Schwalt (1994). Johnson (2000) experimentally worked the scale effects for weir on discharge coefficient for various flat-topped and sharped-crested weirs he show that weirs should be classified based on their physical geometry and the amount of head associated with the flow passing over the weir and also showed that the important variable governing discharge over flat-topped weirs was H/L (where: $H = h + V^2/2 g$, h is a head of water above weir crest and L is a length of the weir). Gogus et al. (2006) carried out experimental works on three sets of step height and three sets of lower weir crest widths. They have studied the effect of width, step height and approach velocity on the coefficient of discharge. Noori and Juma (2010)

experimentally studied the performance of broad crested weir by introducing an upstream face slope, rounding upstream corner and capping the upstream corner with a semi-cylinder in order to reduce the effect of flow separation. They estimated that the value of discharge coefficient in terms of effective head to crest height ratio, upstream corner radius to crest height ratio and radius of cap to crest height ratio. Castro-Orgaz et al. (2010) investigated that the critical depth of flow over broad weir depending of two approaches, the first based on the minimum specific energy of surface streamline and the second based on the mean energy head of the whole flow section. They found a large differences between the dimensionless critical depths were obtained with the two methods. They conclude that each critical depth was a different control point on the free-surface profile of the flow over the broad weir. Salmasi et al. (2011) investigated the effects of width of lower weir crest and step height of broad crested weirs with rectangular compound cross section on the values of the discharge coefficient and the approach velocity coefficient. They obtained that the values of discharge coefficient were lower than those of a broad crested weir with a rectangular cross section because of its contraction effects. Goodarzi et al. (2012) experimentally investigated the hydraulic characteristics of flow over rectangular broad crested weirs with varying upstream slopes. The results showed decreasing upstream slopes from $90^0$ to $10^0$ leading to increasing discharge coefficient values and dissipation of the separation zone. Zachovol et al. (2012) studied the characteristic of flow separation at the upstream edge of broad crested weir, their study based on Particle

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Image Velocimetry. They have described the shape of the time-mean eddy in the separation zone by means of polynomial equation. On the other hand, one may realize that from the previous studies, that investigation on the effect of roughness on the different type weirs is relatively few. Othman *et al*. (2011) performed an experimental studied on effect of size and surface roughness of cylindrical weirs on discharge coefficients under different flow conditions. Their obtained results show that discharge coefficient values will increase in surface roughness of weir with increase in cylinder diameter. An empirical relation was obtained to estimate the coefficient of discharge under different roughness. The influence of surface roughness on the discharge coefficient of a broad crested weir was studied theoretically and compared with experimental research carried out at the laboratory by Parilkova *et al*. (2012). In additionally, Ghobadian *et al*. (2013) experimentally investigated the effect of crest roughness on flow characteristics over circular weirs. The results showed that for a constant discharge, as the weir surface roughness increases the upstream water level over the weir increases and the discharge coefficient reduces. Also, the increased roughness makes the velocity profile over the weir more uniform, with a higher average velocity and the effects of roughness on velocity values were less near weir in comparison with water surface.

However, in the available previous studied sources the discharge coefficient of broad crested weirs is usually expressed for a smooth crest. The present study have been summarized experimentally the effect of actual height of surface roughness on the performance of broad crested weirs.

## LITERATURE REVIEW

The Energy and continuity equations are the theoretical base of the free flow over broad crested weir. Theoretically if no energy lost, a well-known equation for evaluating the discharge has been written in literatures and formulated as in Eq. (1):

$$Q_{th} = \frac{2}{3}\sqrt{2g}BH^{3/2} \tag{1}$$

where, $Q_{th}$ is the theoretical discharge over the weir ($L^3/T$), B is width of channel (L), H is total head, H is h + $V^2/2g$ (L), h is head of water above weir crest (L), V is velocity of flow upstream ($LT^{-1}$) and g is gravitational acceleration ($LT^{-2}$). The actual value of discharge is affected by all the factors imposed in the flow phenomena. The proportion of the actual to the theoretical values of discharge is well known as coefficient of discharge $C_d$ Eq. (2). This coefficient simulates the effect of all factors entering the physical process of flow:
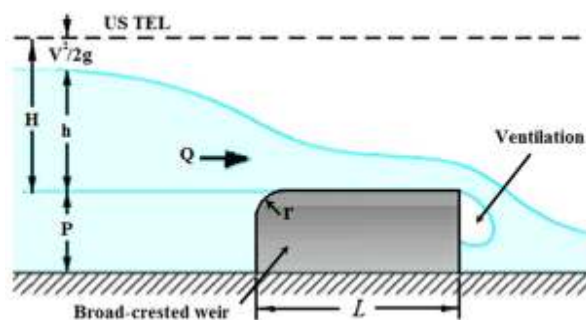


Fig. 1: Broad crested weir

$$C_d = \frac{Q_{act.}}{Q_{th}} \tag{2}$$

where, $C_d$ is coefficient of discharge and $Q_{act}$ is the actual discharge passing gate opening ($L^3/T$). The flow over broad-crested weir with roughness surface expected to be a function of the following variables, as shown in Fig. 1:

$$Q_{act} = f_1(H, L, r, B, P, K_s, g, \rho, \mu, \sigma) \tag{3}$$

where, L is length of the weir (L), r is radius of upstream of the weir (L), P is weir height (L), Ks is roughness size ($D_{100}$)(L), $\rho$ is mass density of water $ML^{-3}$ and $\mu$ is viscosity of water ($MT^{-1}/L$). Based on the Eq. (3) and using dimensional analysis, the following functional relationship of dimensionless parameters can be obtained:

$$C_d = f_2\left(\frac{H}{L}, \frac{H}{r}, \frac{H}{K_s}, \frac{H}{P}, \frac{H}{B}, \frac{L}{K_s}, \frac{K_s}{P}, Re, We\right) \tag{4}$$

The values of Reynolds number and Weber number are not affected due to turbulent flow and neglecting surface tension.

## METHODOLOGY

**Experimental work:** Three models of broad crested weirs were constructed from wood; each model had 10 cm height and 7.6 cm width with different values of length (L = 20, 25 and 30 cm, respectively). In each model, the surface was roughed four times as: $K_s$ = smooth, 2.36, 3.35 and 4.75 mm, respectively (i.e., $D_{100}$ = 2.36 mm, $D_{100}$ = 3.35 mm and $D_{100}$ = 4.75 mm, where: $D_{100}$= the sieve diameter in which 100% of material are finer), Fig. 2, each model was installed horizontal and fixed by attached hook in a rectangular flume bottom, having 2.4 m length, 7.6 cm width and 25 cm depth. The flow rate was measured by a volumetric tank. At the beginning of each run, water entered the inlet tank from a sump fed by pump and controlled manually by a valve (Fig. 2).

Fig. 2: Broad crested weir model

Table 1: Details of the broad crested weir models tested during the experimental program

| Models | Weir length L (m) | State of surface Ks (mm) |
|--------|-------------------|--------------------------|
| 1 | 0.20 | Smooth |
| | | 2.36 |
| | | 3.35 |
| | | 4.75 |
| 2 | 0.25 | Smooth |
| | | 2.36 |
| | | 3.35 |
| | | 4.75 |
| 3 | 0.30 | Smooth |
| | | 2.36 |
| | | 3.35 |
| | | 4.75 |

Different flow rates were allowed by gradually opening the valve. In each run, the flow rate was recorded and the normal water depth was measured vertical to the crest weir using a point gauge. Details of the experimental program are shown in Table 1.

**RESULTS AND DISCUSSION**

The data collected from the tests of the three models and four roughness heights are presented in Fig. 3, which shows that two lengths of weir and four different height of roughness. It is clear that the discharge flowing over broad crested weir decrease with increases of roughness height (Ks) within the experimental range. This reduction caused by the head loss due to increase of surface resistance force.
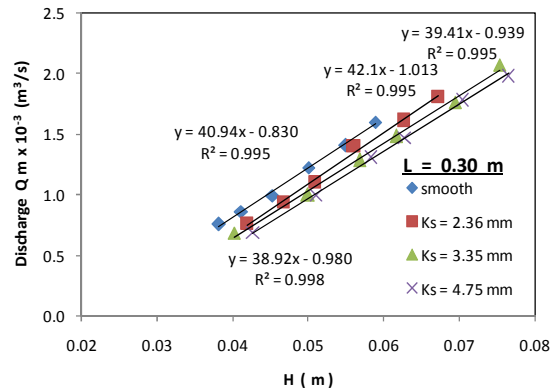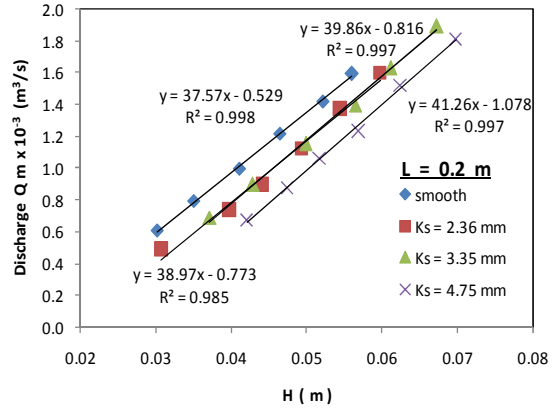


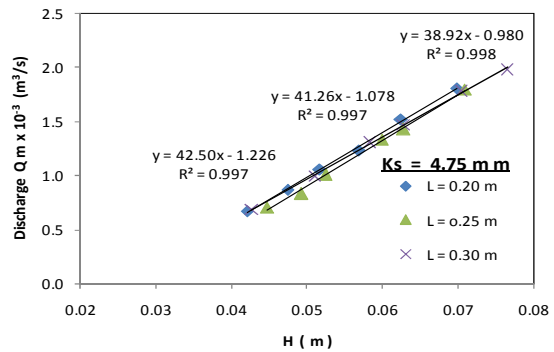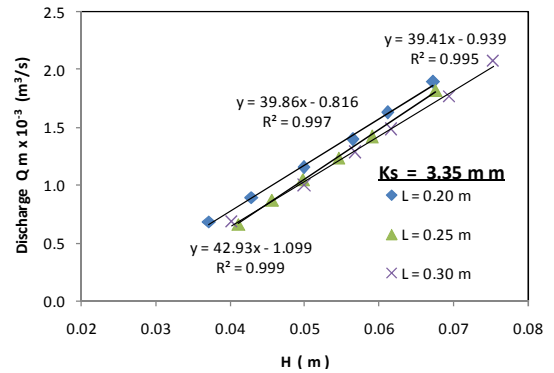Fig. 3: Variation of the discharge with total head for different weir length





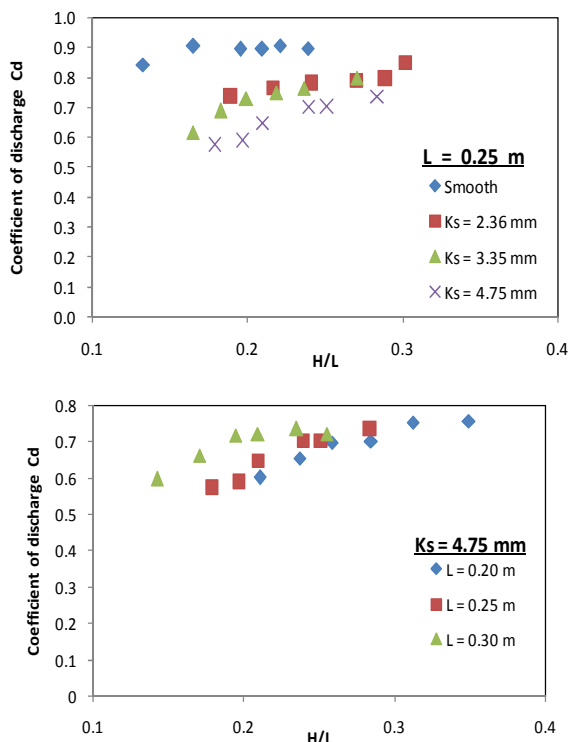Fig. 4: Variation of the discharge with total head for different roughness

Fig. 5: Variation of the discharge coefficient and H/L for different Ks

Also, it can be notes that there is a logical trend of increasing discharge with the increase of the total head acting of the broad weir. The experimental data is also presented in other way to observe the effect of weir length on the discharge for the same roughness.

Figure 4 shows that there is a slight increase in discharge value with the decrease of weir length for different values of roughness height (Ks).

The calculated value of discharge coefficient $C_d$ in Eq. (2) was studied with the dimensionless parameters in Eq. (4). It is clear that the value of $C_d$ increases with the increase of H for a fixed value of L and increases with the decrease of surface roughness Ks, Fig. 5 shows the relation. It can be also noticed that for a fixed value of surface roughness the value of $C_d$ decreases with decrease of weir length.

The measured physical quantities within the experimental limitations of threeweir length and four roughnessesare listed in Excel sheets to calculate the dimensionless parameters in Eq. (4). The calculated discharge coefficient $C_d$ from Eq. (4) varies in the range from 0.5735 to 0.9375, with Standard Error 0.0104873 and Standard Deviation 0.0889875. Some of the descriptive analysis for $C_d$, H/L and H/Ks are shown in Table 2. The facilities built in the features of SPSS 17 (statistical software package) are employed to get statistical analysis and mathematical relations between the variables. The correlation between the depentent variable $C_d$ with the calculated dimiensionless parameters was studied, it was found that only four independedNt parametres (H/L, H/Ks, L/Ks, Ks/P) have a significant correlation at the 0.01 level (2-tailed), while the other three parameter (H/r, H/P, H/B) haven't significy on $C_d$ even at 0.05 level (2-tailed), but there are correlated to the first four dimensionless parameters at 0.01 level (2-tailed) in the correlation matrix. The highest positve Pearson Correlation factor is 0.651

Table 2: Descriptive analysis of the calculated coefficient of discharge and Fr

Descriptive statistics

| | N statistic | Range statistic | Min. statistic | Max. statistic | Mean statistic | Mean S.E. | S.D. statistic | Variances statistic |
|---|---|---|---|---|---|---|---|---|
| cd | 72 | 0.3640 | 0.5735 | 0.9375 | 0.769652 | 0.1048730 | 0.0889875 | 0.008 |
| H/L | 72 | 0.2219 | 0.1274 | 0.3493 | 0.217525 | 0.0060900 | 0.0516753 | 0.003 |
| H/Ks | 72 | 0.0047 | 0.0001 | 0.0048 | 0.002640 | 0.0002011 | 0.0017065 | 0.000 |
| Valid N (lis twise) | 72 | | | | | | | |

Min.: Minimum; Max.: Maximum; S.E.: Standard error; S.D.: Standard deviation

Table 3: The regression models analysis

| No. | Equation | $R^2$ |
|---|---|---|
| 1 | $Cd = 0.714 + 0.86\dfrac{H}{L} - 49.606\dfrac{H}{Ks}$ | 0.861 |
| 2 | $Cd = 0.714 + 0.86\dfrac{H}{L} - 4.961\dfrac{Ks}{P}$ | 0.861 |
| 3 | $Cd = -2.149 + \left(\dfrac{H}{L}\right)^{0.303} + \left(\dfrac{H}{Ks}\right)^{-0.028} + \left(\dfrac{L}{Ks}\right)^{0.16}$ | 0.789 |
| 4 | $Cd = 0.721\left(\dfrac{H}{L}\right)^{0.236}\left(\dfrac{H}{Ks}\right)^{-0.065}$ | 0.781 |
| 5 | $Cd = 0.727\left(\dfrac{H}{L}\right)^{0.237}\left(\dfrac{H}{Ks}\right)^{-0.061}\left(\dfrac{L}{Ks}\right)^{0.004}$ | 0.781 |
| 6 | $Cd = 0.429\left(\dfrac{H}{Ks}\right)^{-0.2171}\left(\dfrac{L}{Ks}\right)^{-0.163}$ | 0.620 |
| 7 | $Cd = 0.649 + 1.707\left(\dfrac{H}{L}\right)^{2} + 2.19\times10^{-8}\left(\dfrac{H}{Ks}\right)^{2} + 0.01\left(\dfrac{L}{Ks}\right)^{2}$ | 0.515 |

between the $C_d$ and L/Ks, while highest negative Pearson Correlation factor is 0.797 between the $C_d$ and H/Ks.

The Regression facilities of the SPSS sotfware was used to find correlation models between the dependent $C_d$ variable and the indepent paramiters in Eq. (4). The molels studied includ 16 mathmatical relations of three type's models, linear, square and power. The best and simplest forms of equations were the linear models; they have the high coefficient of determination equal to 0.861. Nonlinear Regression shows that the square and power models haven't very high value of $R^2$, the highest power equation has $R^2$ is equal to 0.789. To show some of the models, 7 models have been chosen Table 3.

The first and second equation in the table are the simplest withthe hieghest $R^2$ equale 0.861. They have

been found by the regression of the data of $C_d$ assusieted with 6 dimensionsless parameters using stepwise method of including independent varables in linear modele to determing statisticaly signifucnce 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 two indepentent varibles stopped with $R^2$ is 0.861 and stadard Error of estimate equle to 0.03377120:

$$C_d = 0.714 + 0.86\frac{H}{L} - 49.606\frac{H}{Ks} \qquad (5)$$

The statistical analysis output details for the proposed Eq. (5) are shown in Table 4 and 5. The plot of the normal P-P regression standardized residual as shown on Fig. 6.

Table 4: Stepwise regression analysis

Model summary[b]

| Model | R | $R^2$ | Adjusted $R^2$ | S.E.E. |
|---|---|---|---|---|
| 1 | 0.797[a] | 0.635 | 0.630 | 0.0541532 |
| 2 | 0.928[b] | 0.861 | 0.856 | 0.0337120 |

ANOVA[c]

| Model | | S.S. | df | M.S. | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 0.357 | 1 | 0.357 | 121.720 | 0.000[a] |
| | Residual | 0.205 | 70 | 0.003 | | |
| | Total | 0.562 | 71 | | | |
| 2 | Regression | 0.484 | 2 | 0.242 | 212.853 | 0.000[b] |
| | Residual | 0.078 | 69 | 0.001 | | |
| | Total | 0.562 | 71 | | | |

[a]: Predictors: (constant), H/Ks; [b]: Predictors: (constant), H/Ks, H/L; [c]: Dependent variable: cd; S.E.E.: Standard error of the estimate; S.S.: Sum of square; MS.: Mean square

Table 5: Stepwise regression coefficients

Coefficients[a]

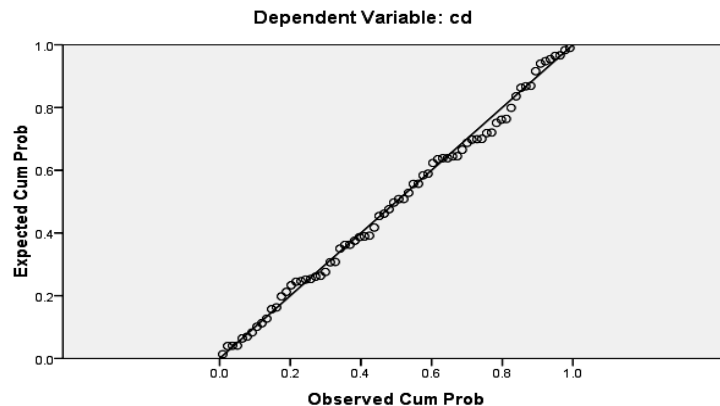| Model | | Un-standardized coefficients | | Standardized coefficients | | |
|---|---|---|---|---|---|---|
| | | B | S.E. | β | t | Sig. |
| 1 | (Constant) | 0.879 | 0.012 | -0.797 | 74.428 | 0.000 |
| | H/Ks | -41.551 | 3.766 | | -11.033 | 0.000 |
| 2 | (Constant) | 0.714 | 0.017 | | 41.161 | 0.000 |
| | H/Ks | -49.606 | 2.465 | -0.951 | -20.121 | 0.000 |
| | H/L | 0.860 | 0.081 | 0.500 | 10.565 | 0.000 |

[a]: Dependent variable: cd



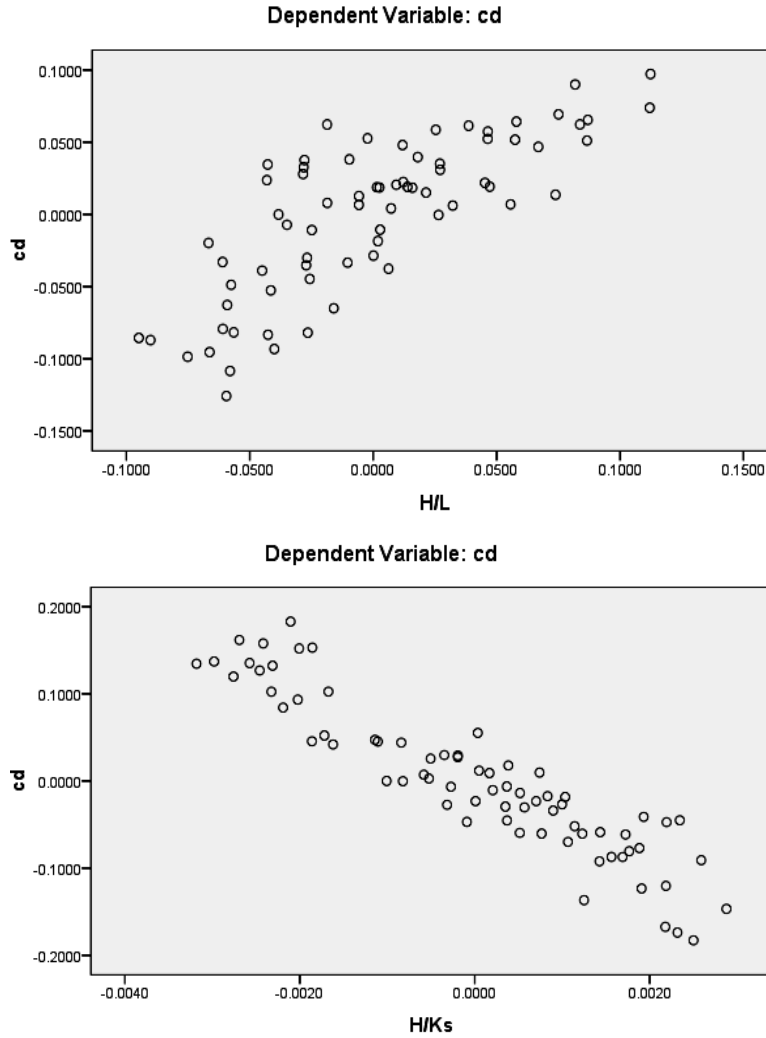Fig. 6: Normal P-P plot regression standardized residual

Fig. 7: Variation dependent variable of Cd with the independent variables H/L and H/Ks

Table 6: Regression of linear model

Model summary[b]

| Model | R | $R^2$ | Adjusted $R^2$ | S.E.E. | $R^2$ change | F change | df1 | df2 | Sig. F change | Durbin-watson |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Change statistics | | | | | |
| 1 | 0.993[a] | 0.986 | 0.985 | 0.0000507 | 0.986 | 4776.487 | 1 | 70 | 0.000 | 0.735 |

[a]: Predictors: (constant), Qca; [b]: Dependent variable: Qm; S.E.E.: Standard error of estimate

Table 7: The significance of the relation

ANOVA[b]

| Model | | S.S. | df | M.S. | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 0.000 | 1 | 0.000 | 4776.487 | 0.000[a] |
| | Residual | 0.000 | 70 | 0.000 | | |
| | Total | 0.000 | 71 | | | |

[a]: Predictors: (constant), Qca; [b]: Dependent variable: Qm; S.S.: Sum of square; M.S.: Mean square

The statistical plots of the dependent variable $C_d$ and the independent variables H/L and H/Ks are present in Fig. 7, which shows increasing trend with H/L and the decreasing trend of with H/Ks.

The proposed Eq. (5) for prediction $C_d$ is checked by calculation the value of discharge. The calculated values of discharge from Eq. (5) are analyzed by linear regression with measured discharge. It has been found a significant correlation at the 0.01 level (2-tailed) with Adj. $R^2 = 0.986$. The model summery and ANOVA tables which shows the relation of the regrresion between the actual (measured) discharge and the

calculated value from $C_d$ and theoretical discharge are shown in Table 6 and 7. It is clear that the value of F-statistics is very hiegh.

## CONCLUSION

The flow over broad cristed weir with a surface roughness was studied experimantaly in open channel by changeing the length of weir. From statistical analysing of experimental data the following conclusions may forwarded:

- The increase of surface roughness has a negative effect on the performance of the broad weir.
- The value of $C_d$ increases with the increase of H/L.
- The value of $C_d$ decreases with increases H/Ks or Ks/P.
- The value of $C_d$ range from 0.54 to 0.94, with Standard Error 0.0104873.
- Within the limitations of the present experimental work a discharge prediction Eq. (5) is developed with mean percent error of 0.0507%.

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