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Flow Characteristics of Sharp Crested Rectangular Weir: A Review

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ABSTRACT
Sharp crested weirs are widely used as discharge measuring device in laboratories, industries and irrigation channels. From many years sharp crested rectangular weirs has been investigated by many researchers. The common objective of these studies was to investigate the flow behaviour of the weirs and obtain the discharge coefficient. Analysis of water surface profile and measurement of head over the weir crest are the important aspects in discharge analysis through sharp crested weirs. Width of the weir opening (b) and the weir height (P) affect the coefficient of discharge and thereby the discharge also. In the present paper the works carried out in this field have been studied till date. It is also mentioned what work can be carried out in future by studying and analyzing the past work.

Key words: Open Channel Flow, Sharp Crested Weir, Reynolds number, Coefficient of Discharge,

1. INTRODUCTION

Measurement of discharge in open channels plays a vital role in the equal distribution of water among the users in field and accordingly charging correct amount from them by metering the flow. The measurement of flow in open channels is generally made by means of weirs or sluice gates. In large open channels or natural streams, the flow is estimated by dividing the flow section into number of smaller sections and determining the average velocity for each section by means of current meter. Various methods are available for the determination of discharge in open channel and can be broadly classified into two groups:

(i) Direct determination

(ii) Indirect Determination

The direct determination of discharge includes various methods like area velocity method, dilution techniques, electromagnetic method and ultrasonic method. The indirect determination of discharge includes hydraulic structures like weirs, flumes, gated structure, end depth ratio method and slope area method.

Weirs are also used to measure discharge in open channels by using the principle of rapidly varied flow. They are extensively used in open channels in irrigation canals, laboratories, industries, and also used as dam instrumentation device. Weirs are most commonly used due to their simplicity and ease in construction, durability and accuracy in measurement.

2. WEIR

Weir is a standard device for the measurement of flow in open channel since last two centuries. It is an obstruction in the path of flow that causes the liquid to rise behind the weir and then flows over it. By measuring the head of water over the weir the quantity of discharge can be estimated by using well established head-discharge relationship. If the jet of liquid passing over the weir springs free as it leaves the upstream face, the weir is known as sharp crested weir, while broad crested weirs are those which support the falling nappe over its crest, in the longitudinal direction and critical depth occurs over the weir.

On the basis of shapes the weirs can be classified as the rectangular, triangular, trapezoidal, parabolic, etc. and are given below:

- Sharp crested rectangular weir
- Broad crested weir
- V-notch weir
- Labyrinth weir
- Compound weir
- Minimum energy loss weir
- Sutro weir

Amongst the above mentioned weirs, sharp crested rectangular weir, v-notch and broad crested weir are most common.

3. SHARP CRESTED RECTANGULAR WEIR

Sharp crested rectangular weir is a thin vertical plate provided in an open channel to estimate the discharge. The edge of the sharp crested weir is bevelled on the downstream side to give a minimum contact with the liquid. The thickness of weir at the crest is about 0.2 times the thickness of the weir plate and overall thickness of plate is about 2 mm. In the downstream side the bevelled surfaces should make an angle between 45^0 to 60^0. The rate of flow is determined by measuring the head over the weir crest (H) at a distance sufficiently upstream at least three to four times the head to be used [2].

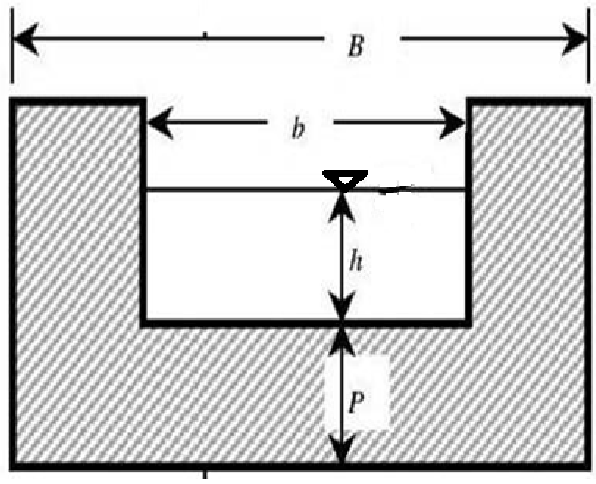

Fig.1 Front view of Contracted Sharp Crested Rectangular Weir

The pattern of flow over thin plate weir is very complex and cannot be analyzed theoretically alone. This is due to the non hydrostatic pressure distribution, turbulence, and frictional effects, and the approach flow conditions. The effect of viscosity and surface tension also becomes important at low heads. Therefore the analytical relation between Q and H is obtained after some simplifying assumptions and suitably modifying by experimentally determined coefficients (C_d).

4. Contracted Rectangular Weir: When the width of the crest (b) of a rectangular weir is less than the width of the channel (B), then there will be contraction of the nappe in lateral direction also so that the length of the nappe is less than the channel width. Such types of weirs having end contractions are called as contracted weirs.

TYPES OF SHARP CRESTED RECTANGULAR WEIRS

Full width weirs: A weir which extends across the full width of the rectangular approach channel (B/b=1.0). In literature this weir is frequently referred to as a rectangular suppressed weir or Rehbock weir. For suppressed rectangular weir, discharge equation can be derived and is given below[22]:

$$Q = \frac{2}{3} C_d \sqrt{2g} B H^{3/2} \qquad (1)$$

Where, Q is discharge through weir in m^3/s, g is acceleration due to gravity in m/s^2, B is width of weir in m, H is the head over weir crest in m and C_d is coefficient of discharge. However for contracted weir, B is replaced by b.

Partially contracted weir: A weir the contractions of which are not fully developed due to the proximity of the walls and the bottom of the approach channel is called as partially contracted weir.

Fully contracted weirs: A sharp crested weir which has an approach channel whose bed and walls are sufficiently remote from the weir crest and sides for the channel boundaries to have no significant influence on the contraction of the nappe. For fully contracted rectangular weir discharge is given as [22 pp. 756]:

$$Q = \frac{2}{3} C_d \sqrt{2g} (b - 0.1nH) H^{3/2} \qquad (2)$$

Where, b is contracted width of the weir and n is number of end contractions.

BRIEF LITERATURE REVIEW

Till now a lot of works have been carried out by various investigators on sharp crested weirs in different shapes of weirs. Research works highlighting the assumptions, principle, equations used and modelling techniques involved along with results and conclusions are discussed here in brief. Both experimental and analytical work carried out in this field till date has been discussed in detail.

Rehbock [32] in 1929 carried out experimental work with full width sharp crested rectangular weirs. He concluded that the discharge coefficient C_d depends upon the head over the weir crest (H) and the weir height (P), while neglecting the viscous and surface tension effects. The empirical equation for discharge coefficient (C_d) is given below:

$$C_d = 0.611 + 0.08\frac{H}{P} + \frac{H}{1000} \qquad (3)$$

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His formula has been found to be accurate within 0.5% for values of P varying from 0.1 to 1.0 m and for value of H ranging from 0.025 m to 0.60 m with the ratio $\frac{H}{P}$ not greater than 1.0.

Kandaswamy and Rouse [23] in 1936 obtained discharge coefficients on the basis of their experimental results. The results of their study was based on three different ranges of H/P, i.e. H/P ≤ *5*, 5< H*/P* <15 and H*/P* ≥*15*. They proposed the following equation for discharge coefficient in the range of H/P ≥ 15:

$$C_d = 1.06\left(1+\frac{H}{p}\right)^{1.5} \quad (4)$$

Kindsvater and Carter [24] in 1957 made extensive study about rectangular sharp crested weirs. They introduced a number of equations for discharge coefficient as a function of (H*/P*) and (*b/B*). They introduced a parameter of C_e (effective discharge coefficient) which is free from the effect of surface tension and viscosity due to the contraction of water at the weir.

According to Kindsvater and Carter the discharge equation is given as follows:

$$Q = C_e \frac{2}{3}\sqrt{2g}\, b_e H_e^{\frac{3}{2}} \quad (5)$$

In above equation, effective discharge coefficient (C_e) is given by:

$$C_e = 0.602 + 0.075\frac{H_1}{P_1} \quad \text{(Full width weirs)} \quad (5.1)$$

The effective width (b_e) is given as:

$$b_e = b_c + K_b \quad (5.2)$$

And the effective head (H_e) is:

$$H_e = H_1 + K_h \quad (5.3)$$

In above equations (5.2) and (5.3), K_b and K_h represent the combined effects of the several phenomena attributed to viscosity and surface tension. The value of K_b is recommended as 0.001 m for all the values of b_o/B_1 and H_1/B_1. Where b_o and B_1 are the width of weir and width of the channel respectively.

Ranga Raju and Asawa, [31] carried out experimental studies and they in 1977 found that the pattern of flow over a thin plate weir is very complex and cannot be analysed theoretically alone. This is due to the non-hydrostatic pressure variation, turbulence, frictional effects and the approach flow conditions. The effect of surface tension and viscosity become important at low heads. Following this approach, they obtained the following discharge equation for suppressed thin plate rectangular weir

$$Q = \left[\frac{2}{3}\left(0.611 + 0.075\frac{H}{W_1}\right) b\sqrt{2g}H^{3/2}\right] K_1 \quad (6)$$

Where W_1 is the Weber number and K_1 is the Correction factor to account for the effects of viscosity and surface tension.

Ramamurthy et al. (1987) [28] through their experimental studies concluded that the discharge coefficient (C_d) for flow over a rectangular sharp crested weir in the weir range of $\left(0 < \frac{H}{P} < 10\right)$ and the sill range of $\left(10 \le \frac{P}{H} \le \infty\right)$ can be related to the weir parameter H/P semi empirically. They proposed following expression for C_d as follows:

$$C_d = \frac{3}{4}\left\{\frac{\left(\frac{1+\frac{H}{P}}{\frac{H}{P}}\right)^2 (1-Kf) - Kb\left(\frac{Yb}{H}\right)^2}{\frac{\beta}{\left(\frac{Yb}{H}\right)} - \left[\frac{\frac{H}{P}}{1+\frac{H}{P}}\right]}\right\}^{\frac{1}{2}} \quad (7)$$

Swamee P.K. (1988) [38] proposed a generalized weir equation for sharp-crested, narrow-crested, broad-crested and long-crested weirs by combining the equations obtained from previous works. His equation holds good for extreme variations of H/P ratio and H/b ratio. According to Swamee:

$$C_d = 1.06\left[\left(\frac{14.14P}{8.15P+H}\right)^{10} + \left(\frac{H}{H+P}\right)^{15}\right]^{-0.1} \quad (8)$$

Swamee P.K. (1988) [39] again made extensive experimental studies on rectangular sharp crested weir and proposed a full range expression for C_d in terms of B/b and H/P ratios as follows:

$$Cd = \frac{0.611+2.23\left({}^{B}/_{b}-1\right)^{0.7}}{1+3.8\left({}^{B}/_{b}-1\right)^{0.7}} + \frac{0.075-0.011\left({}^{B}/_{b}-1\right)^{1.46}}{1+4.8({}^{B}/_{b}-1)\text{^}1.46}\frac{H}{P}$$

(9)

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Swamee et al. [40] in 1994 made extensive studies on sub-critical flow over rectangular side weirs and developed an equation for elementary discharge coefficient so as measure the discharge with sufficient accuracy over side weirs. According to them, discharge coefficient (Ce):

$$C_e = 0.447\left[\left(\frac{44.7P}{49P+y}\right)^{6.67} + \left(\frac{y-P}{y}\right)^{6.67}\right]^{-0.15} \quad (10)$$

Where, y = H+P

Rajaratnam et al[28] in 1996 made experimental study on submerged flow over sharp-crested rectangular weirs. He found that the flow has been divided into the two broad classes of impinging jet and surface flow regimes. He developed a diagram to predict the occurrence of these regimes. He also found that the boundaries of these regimes depend upon the direction of change of the tail water.

Aydin et al [2] in 2002 proposed the concept of slit weir (b/B≤0.25) generally used for measuring the low discharges (up to 0.005 m^3/s). They found that the coefficient of discharge (C_d) is a function of Reynolds number (Re) and proposed following equation:

$$C_d = 0.562 + \frac{11.354}{\sqrt{Re}} \quad (11)$$

But his equation has certain limitations i.e. b≤0.005 m and b/B≤0.25.

Martinez et al. [25] in 2005 made studies on compound sharp crested weir consisting of two triangular parts with different notch angles. This weir provides very accurate measurement for a wide range of flow without discontinuities. The lower part of the weir handles the normal range of discharges while the upper part measures the occasional higher discharges.

Aydın et al. (2006) [3] modified their above equation (11) to increase the working range of slit weirs for small values of H/b ratio. They carried out experiments for b ranging from 0.005 to 0.075 m in a channel of width 0.30 m with different values of P. The experimental data covers the range of 0.28≤H/b≤55.80. They proposed an equation for C_d as follows:

$$C_d = 0.562 + \frac{10\left\{1-exp\left[-\left(\frac{2H}{b}\right)^2\right]\right\}^{-1}}{Re^{0.45}} \quad (12)$$

For H/b≥2, a simplified form for C_d is:

$$Cd = 0.562 + \frac{10}{Re^{0.45}}$$

(12.1)

Ramamurthy et al. (2007) [30] proposed the multi-slit concept to remove the limitation on the measuring range of slit weir. The idea was to construct a number (n) of slit weirs side by side so that the discharge of any magnitude can be measured with sufficient accuracy of a slit weir by operating only enough number of slits and closing the others. The minimum spacing required between each slit to prevent any interaction was investigated. They concluded that discharge coefficient depends on Reynolds number for smaller values of R. But for large values of Reynolds number inertia forces are high and viscous forces are negligible, which means that C_d does not depend on Reynolds number. They also showed that the multislit weir can be used to measure wide range of discharge rates. They proposed a functional relation for C_d and discharge equation as follows:

$$C_d = f\left(\frac{nb}{B}, \frac{b}{H}, \frac{H}{P}, R, W, n\right) \quad (13)$$

$$Q = \frac{2}{3} C_d nb\sqrt{2g}H^{\frac{3}{2}} \quad (13.1)$$

Bagheri and Heidarpour (2010) [8] in their recent study on sharp crested weirs presented based on integration of velocity due to free- vortex motion occurred between the upper and lower nappe profiles. Form of the discharge coefficient an expression was developed from the best fit approximations of the measured nappe profiles and is given below:

$$C_d = 0.324e^{[x]} \quad (14)$$

$$\text{Where, } x = \left[0.94\left(\frac{b}{B}\right)\right] \ln\left[1 + \frac{0.73\left(\frac{H}{P}\right)+3.64}{e^{\left(1.18\frac{b}{B}\right)}}\right] \quad (14.1)$$

The above equation was valid for the range of 0 < H/P < 9.4.

Later on Bagheri and Heidarpour [9] revised their equation by enlarging the database and extended the validity range as 0 < H/P < 10.

Vatankhah A.R. (2010) [44] made an extensive experimental study on circular sharp crested weirs and proposed a simple and accurate equation for discharge coefficient as follows:

$$Cd = \frac{0.728+0.240n}{1+0.668\sqrt{n}} \tag{15}$$

Where, n is the relative depth (H/D)

Xin Zhang et al. (2010) [47] made their experimental studies on rectangular sharp crested weirs for clinging flow as well as free flow. They indicated that the transition from clinging to free flow and vice versa do not occur at the same head. They gave an equation for $C_{d,}$ for clinging flow as follows:

$$Cd = \begin{Bmatrix} 0.605 + \frac{1}{1000H} + 0.08\frac{H}{P}, & H_l crit < H \le H_u crit \\ c\left[0.605 + \frac{1}{1000H} + \frac{0.08H}{P}\right] + d, & H \le H_l crit \end{Bmatrix} \tag{16}$$

Where, $H_u crit. is$ upper critical head and $H_l crit.$ is lower critical head.

Aydin et al. (2011) [4] after their experimental studies proposed that the discharge in rectangular weirs can better be formulated in terms of average weir velocity (V_w), which has a universal distribution easy to fit empirically, rather than the discharge coefficient (C_d), which exaggerates the experimental error by changing the curvatures. They also proposed that for precise measurement of H, the maximum velocity in the channel should be limited to 0.55 m/s.

Ferro V. (2012) [17] examined geometrical shapes of sharp crested weirs. A stage discharge relationship was developed for triangular sharp crested weirs using the dimensional analysis and the self similarity theory. He concluded that a power equation can be used for establishing the stage discharge equation with coefficient and an exponent depending upon the weir geometry.

Aydin et al (2014) [5] introduced a physical quantity known as weir velocity i.e. the average velocity over the weir section, which is directly formulated as function of weir geometry and head over the weir. The weir velocity plotted against the weir head has a universal behaviour for constant weir width (b) to channel width (B) ratio (b/B) which is independent of weir size. This unique behaviour described in terms of weir parameters to calculate the discharge without involving the discharge coefficient.

Weir velocity is given as follows:

$$V_w = C_d \frac{2}{3}\sqrt{2gH} \tag{17}$$

$$Q = V_w(bH) \tag{17.1}$$

Bagheri and Heidapour (2014) [10] made studies on sharp crested weirs and introduced a novel sharp crested weir design with sinusoidal notches. They found that the discharge coefficient of the sinusoidal weir can be assumed as constant (approximately 0.57) in the complete head discharge equation. He also found that sinusoidal weirs provided an efficient passage of floating debris, with consequent reduction in sedimentation. This weir design may also benefit the fish way design.

CONCLUSION AND FUTURE SCOPES

Flow measurement in any open channel flow is a vital aspect of its design and levy charged by the users. Sharp crested weir is a simple device for estimation of discharge in all shapes of channels. Till now it has always taken an attention by various researchers and a number of works have been carried out in this field. During the literature review, it was found that a lot of work has been carried out till date on various shapes of sharp crested weirs like rectangular, triangular, circular etc.

1. From the above description it is clear that, a lot of work has been done in the field of sharp crested rectangular weir. But in case of contracted sharp crested rectangular weir sufficient work had been not done yet and further more work could be done.
2. There is a further scope to carry out the discharging characteristics of contracted sharp crested weir in terms of weir velocity and for slit weirs.
3. There is still more scope for study of the discharge characteristics of the trapezoidal weirs.
4. Similarly further work can be done for different bed width (B) channels.

5. Similar works could be done for studying the effect of channel slope in the discharge equation of sharp crested weirs.

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