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Development of Rectangular Broad-crested Weirs for Flow Characteristics and Discharge Measurement

Kiumars Badr* and Dariush Mowla**

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Abstract

One of the important problems which designers and engineers are faced with is proper measurement of water flow rates in open channels and rivers. To solve this problem, the water discharge to be precisely measured in water conveyance systems such as off takes and distribution ditches. The common procedure to meet this requirement is achieved by using water-measuring structures such as flumes, orifices, weirs and current meters. Among the mentioned structure, engineers prefers the weirs because of their simple structure and economical features. The broad-crested rectangular weirs are very common which are widely used in water ways and canals. In this study, the effect of steeping in the upstream side of rectangular broad-crested weirs over discharge coefficient and flow characteristics is investigated. Five weirs with 15, 30, 45, 60 and 90 weir angles were developed and flow discharge coefficient, negative velocity over the weir crest edge and water surface profiles along the weir crest evaluated in laboratory hydraulic flume. The obtained results showed by decreasing the slope of the upstream side, discharge efficiency and the discharge capacity of the weir are increased subsequently. Consideration of experimental data it is obvious that by using the proposed weir with slope of 15 degree in comparison with standard weir, the efficiency is increased up to 19.17%. It is noteworthy that by reducing the slope, return current on the crest is not observed.

Keywords: *discharge coefficient, rectangular broad-crested weir, weir with slope, negative velocity*

1. Introduction

Flow measurement is the quantification of fluid movement parameters. Since the early days of hydraulics, various flow measuring devices such as hydraulic structures have been developed and used in waterways. Hydraulic structures have been installed in open channels or rivers with a free water level to estimate discharge based on the measured upstream water level (Boiten, 1993). Weirs are simple structures that are used to modify flow characteristics in streams and waterways. Rectangular broad-crested weirs are measurement structures that usually have been made of cement concrete. They are used to measure and modify flow characteristics in rivers and artificial channels. Some of the most common broad-crested weirs are rectangular broad-crested weirs with 90 upstream side slope, rectangular round edged broad-crested weirs, and triangular broad-crested or crump weirs. Among these weirs, the simplest is the square-edged weir (edge refers to the entrance from the approach channel) with rectangular cross section. The main advantages of rectangular broad-crested weirs with 90 upstream side slope include constant discharge coefficient in optimum flow condition, less sensitivity to downstream submergence, simple design and construction, and low construction and utility costs.

In particular situations, the weir's structural design can present some flexibility for modifying the upstream side slopes to provide better hydraulic characteristics and measure discharge efficiency at higher precision. Hence, different models of broad-crested weirs with a rectangular compound cross section were analyzed experimentally in this study.

The flow characteristics of broad-crested weirs with different cross sections have been of interest to many researchers. Woodburn (1932) showed that flow passes through a critical stage at some section at the crest of a broad-crested weir and the location of this section varies according to hydrostatic head and weir dimensions. In addition, he presented a depth-discharge relationship based on the relationships between overflow capacity, discharge coefficient, weir width, and the upstream water head. Govinda Rao and Muralidhar (1963) classified rectangular weirs in four categories based on the total energy head upstream of the weir H_1 and the crest length L as follows: rectangular long-crested weirs, rectangular broad-crested weirs, rectangular short-crested weirs, and rectangular sharp-crested weirs. Hall (1962) applied the boundary layer theory and presented a relationship based on the Reynolds number,

*M.Sc, Student, Dept. Chemical Engineering, School of Chemical and Petroleum Engineering, 7134851154, Shiraz, Iran (E-mail: kiumarsbadr@gmail.com)
**Professor, Dept. of Environmental Research Center in Petroleum and Petrochemical Industries, Shiraz University, 7134851154, Shiraz, Iran. (Corresponding Author, E-mail: dmowla@shirazu.ac.ir)

upstream depth and weir crest length. Singer (1964) showed that the elevation changes of weir (P) and weir length (L) is the effective on the discharge coefficient. Harrison (1967) presented a new coefficient of discharge for a streamlined broad-crested weir based on the critical flow theory. Rao and Shukla (1971) carried out an experimental investigation measuring the effect of finite crest length on discharge characteristics of broad-crested weirs with 90 upstream side slope. Isaacs (1981) investigated and examined calm boundary layer effects on a model of broad-crested weir. The results indicated a significant effect the limit layer on the flow characteristics. Ramamurthy *et al.* (1988) studied the effects of rounding the upstream edge of a broad-crested weir on flow characteristics through experimental investigation. Hager and Schwalt (1994) showed that the broad-crested weir with 90 upstream side slope is more accurate than with a round-edged upstream side. Baylar and Emiroglu (2002) studied the air entrainment rate of a 30 triangular sharp-crested weir and compared the results with other sharp-crested weirs with different cross-sectional geometry. Ghodsian (2003) investigated the hydraulics of sharp-crested rectangular side weirs under supercritical flow. Farhoudi and Shahalami (2005) proposed the flow pattern governing hydraulic principles of rectangular broad and short-crested weirs. Borghei *et al.* (2006) studied oblique rectangular sharp-crested weirs for submerged and free-flow conditions and a stage discharge relationship was developed based on the ISS theory. Farhoudi and Shokri (2007) experimentally determined the flow characteristics of the broad-crested rectangular weirs with a sloped downstream side. They considered the effects of downstream slope on weir discharge efficiency and its sensitivity to downstream submergence ratio. Ramamurthy *et al.* (2009) applied a k-ε model to determine various flow characteristics such as velocity distribution, water surface profile and pressure distribution over a sharp-crested weir in a rectangular open channel. Sargison and Percy (2009) investigated the flow of water over a trapezoidal broad-crested or embankment weir with varying upstream and downstream slopes. In their study, the effect of 2H:1V, 1H:1V and vertical slopes in various combinations on the weir upstream and downstream sides were compared. Haun *et al.* (2011) applied two Computational Fluid Dynamics (CFD) codes, Flow 3D and SSIIM2, to calculate the water flow over a trapezoidal broad-crested weir.

Many studies, including those referenced above, have considered the effects of different broad-crested weir designs on flow characteristics, while only few studies in literature investigated a wide range of varying upstream slopes in rectangular broad-crested weirs (i.e., from 90 to 15). Hence, the present study intends to (1) determine the effects of changing the upstream slope of a rectangular broad-crested weir on discharge coefficient, (2) model the flow characteristics of weirs and determine the variation of model constant coefficients with weir geometry and (3) investigate changing velocity profiles over the crest of different sloped weirs along the flow direction and the effect of a region of return currents.

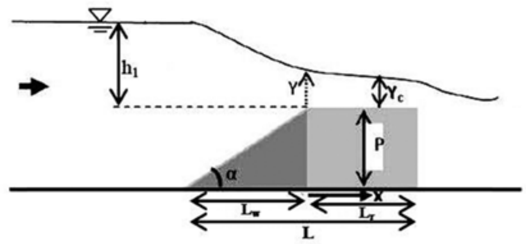

Fig. 1. Parameters of a Broad-crested Weir with Slope in Upstream Side

2. Theoretical Considerations

Rectangular broad-rested weir design was made in according to two primary conditions:

1. The minimum depth of 5 cm over the weir to reduce the effect of viscosity and surface tension.
2. Establishing following ratios:

$$0.08 \le \frac{h_1}{L} \le 0.33, \frac{h_1}{h_1+P} \le 0.35 \tag{1}$$

Figure 1 illustrates the definition of broad-crested weir parameters. Let the theoretical discharge equation of the proposed weir take the form:

$$Q_t = \left(\frac{2}{3}\right)^{3/2} \sqrt{g} B h_1^{3/2} \tag{2}$$

where, B = Width of weir (in the direction perpendicular to the flow direction)
g = Acceleration of gravity
h_1 = The overflow head upstream of the weir
Q_t = The theoretical discharge

The theoretical discharge is greater than the actual discharge due to contraction and friction. The actual discharge relationship was obtained from the theoretical discharge using Eq. (2) after evaluating the coefficient of discharge from the experimental runs as:

$$Q_a = C_d\left(\frac{2}{3}\right)^{3/2} \sqrt{g} B h_1^{3/2} \tag{3}$$

where, Q_a is the actual discharge in $m^3\ s^{-1}$; C_d is the dimensionless coefficient of discharge and is given by

$$C_d = Q_a/Q_t \tag{4}$$

Standard weirs of 90 degree, at the beginning of crest, and at the meeting point of flow with the beginning edge of crest, due to flow separation, region with eddy current are created. Existence of vortices in this area causes, return currents in contrast to main flow are created. The most important effect of these vortices is that the useful cross section (A_u) of flow is reduced. It should be noted that useful cross section of flow is attained from crossing depth of flow to width of weir:

$$A_u = h_1 \times B \tag{5}$$

On the other hand the weir width is also constant during the experiments, it is clear that the depth of flow is reduced. So at a constant flow rate, stream head is increased. Therefore, according to the inverse relationship between the discharge coefficient and stream head (Eq. (3)), by increasing the stream head, the discharge coefficient has been decreased.

Flows that were closed to the weir had a kind of sub-critical flow that after reaching to the weir, the specific energy of flow was increased and thus the depth of flow had been reduced. By steeping weir in the upstream side, the curvature of flow lines that be closed to the weir was decreased, so fewer changes in the depth and velocity of flow had been observed because existing low downfall on the flow level. Generally in broad-crested weir, due to the large length of weir in the flow direction, the curvature of flow line is trivial and distribution of pressure over weir is nearly hydrostatic pressure.

In standard broad-crested weir, at crest and in the meeting point of stream with weir, because of the non-slip properties that is the characteristics of continuous flow, the velocity is zero. While in the weir with slope in the upstream side, velocity at the crest and at the meeting point of water with the crest will not be zero.

3. Method and Materials

Experiments are performed in a glass flume 0.25 m wide, 0.50 m high and 10.0 m long (Fig. 2). Low tail water level was maintained, and it did not affect the oncoming flow for all cases. Weirs used in the experiments are made of Plexiglas . The weirs were constructed from two main parts: the upstream side or wedge section, and the rectangular part or core segment, in which the upstream sides were interchanged in order to produce different combinations of upstream slopes and rectangular sections. The central part's length was 0.59 m (or L_r = 0.59 m) while height and width were 0.26 m and 0.25 m Respectively (or P = 0.26 m, B = 0.25 m). The rectangular section was prepared and secured as the structure's central core across the whole flume width with 1.2 m distances from the upstream water entrance tank. Furthermore, five wedges with different slopes and sizes were prepared and added to the central structure core in each individual experiment layout. Sizes of wedges are presented in Table 1.

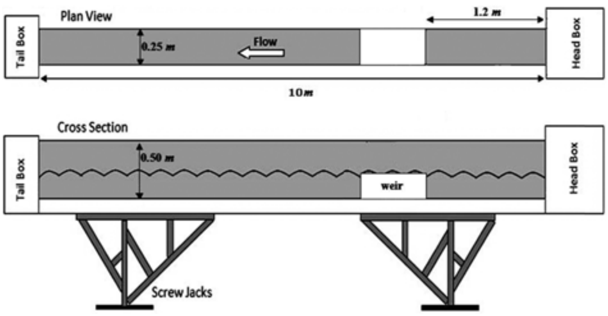

Fig. 2. Experimental Channel

Table 1. Sizes of Weirs used in Experiment (weir height(P) = 0.26 m, $L_r + L_w = L$)

Upstream side slope of rectangular broad-crested weir, (α)	90	60	45	30	15
Weir Length(L) m	0.59	0.74	0.85	1.04	1.56
Wedge Length(L_w) m	0	0.15	0.26	0.45	0.97

Waterproof glue was carefully applied for water tightening of the upstream side. The flow was led to the flume through an upstream tank which was fed from a main reservoir and controlled by an adjustable tool. In the next step, flow with discharges of 20, 25 and 30 liter per second [l s^{-1}] was passed downstream over the weir. It should be noted that the flow rate was adjusted using a pre-calibrated sharp-crested rectangular weir installed at the upstream tank's entrance and volumetric flow rate was measured downstream of the weir using a 90° V-notch weir with an accuracy of ±0.01[l s^{-1}]. In addition, the flume was equipped with a hinged gate to regulate the downstream water depth.

During the tests, after installing the weir in channel and adjusting the flow rate and ensuring the steady flow, depth and flow velocity on the upstream of weir crest and over the weir were measured. The depth of flow over a weir and upstream head was measured by a limnimeter, with the accuracy of 0.1 mm Finally, in each weir, the water surface profile is obtained in three different states over the weir. A pitot tube was used to measure the velocity profiles along the flow direction (such as critical velocity) and over the weir crest.

In order to calculate discharge coefficient at each weir, the stream head in the upstream (h_1) at different flow rates were measured at a distance of 50 cm upstream of weir crest. This distance is based on Bos (1985) proposal is equivalent to 2 to 3 times more than maximum depth (2-3h_{1max}) or 2 to 4 times the height of weir (2-4P).

Fritz and Hager (1998) presented a correction coefficient C_r in the formula of flow over a sharp-crested weir to obtain the flow over a broad-crested rectangular weir with a sloped upstream side as follows:

$$C_r = 1 - \frac{2\sin\alpha}{g(1+\xi^4)} \tag{6}$$

where, in their study, ξ = (h-P)/L, P – weir height, L – crest length, h – depth of flow over the crest, α – the upstream side slope, and C_r – the ratio of weir discharge coefficient with upstream side slope α (C_{d_α}) to discharge coefficient of a standard broad-crested weir ($C_{d_{90}}$):

$$C_r = \frac{C_{d_\alpha}}{C_{d_{90}}} - 1 \tag{7}$$

The discharge coefficient of a rectangular broad-crested weir with an upstream side slope of α can be computed by calculating

C_r from Eq. (6) and applied to Eq. (7).

4. Results and Discussion

In this section by using the measured data has shown the effect of slope on the discharge coefficient and surface profile along the weir and also negative velocity over the crest.

4.1 Investigation of the Effect of Reducing the Slope on the Discharge Coefficient Increase

The free-flow discharge coefficients were computed for all weirs and results revealed that the discharge coefficient increases as the upstream side slope decreases. In other words, the largest discharge coefficient occurred in the weir with upstream side slope of 15 whereas in a standard broad-crested weir (upstream slope of 90) the discharge coefficient was the smallest. The measured discharge coefficients at various flow rates are presented in Table. 2.

Figure 3 shows the correction coefficient (%C_r (Eq. (7))) increases with the slope's changes. According to that figure; as the slope reaches to 45 degree, correction coefficient will increase compared to 90 degrees and on slopes between 45 and 30 (which is the turning point curve) the increase of correction coefficient is very low and trivial about 2.07%. Again from slope of 30 degrees to slope of 15 degrees, we can observe a significant increase in the correction coefficient than the weir correction coefficient of 90 degrees. As in the slope of 15 degrees we have the maximum of flow rate correction coefficient (19.17%) compared to 90 degrees. Based on the results, weirs with a 90 upstream side slope experienced flow separation at the upstream edge, and developing separation zone affected the velocity profile and pressure distribution over the crest. According to the literature, there is an inverse relationship between discharge coefficient (C_d) and the overflow head upstream of the weir (h_1) along the flow direction (Eq. (3)). So, developing the separation zone by increasing flow head would impose a negative effect on the weir's discharge coefficient and it would inversely influence C_d. It was observed that as the upstream side slope decreased, the effect of weir entrance edge on flow separation was diminished.

Table 2. Values of Discharge Coefficient in Different Slope

	Q ($l\ s^{-1}$)		
	20	25	30
Upstream side slopes	Discharge coefficient (C_d)		
90º	0.896	0.909	0.913
60º	0.999	1.007	0.996
45º	1.016	1.018	1.028
30º	1.023	1.037	1.051
15º	1.062	1.093	1.088

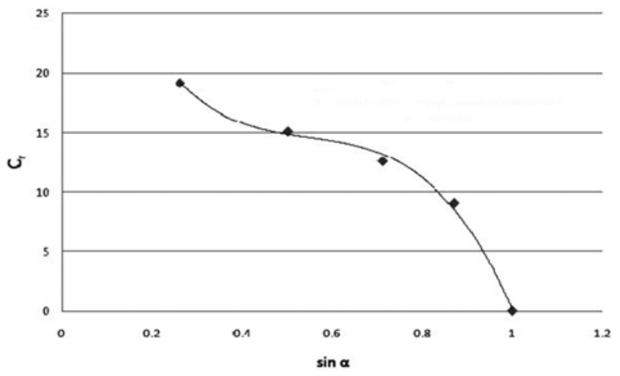

Fig. 3. Changes of Correction Coefficient in Different Slope (Q = 30($l\ s^{-1}$))

4.2 Checking the Flow Profile

A mathematical definition was revealed for the flow profile over individual weirs as follows:

$$H = a - b \times \tanh(X - c) \tag{8}$$

In Eq. (8), flow profile level H(X) is a function of X, where $X = x/h_1$, $H = h/h_1$, x is the distance from the weir's entrance edge (or the edge of the weir's central part), h is the overflow head, h_1 is the overflow head upstream of the weir, and a, b and c are constant coefficients for each weir, as shown in Table 3.

The flow profiles are sketched based on experimental results obtained from all weirs at varying flow rates. Figs. 4 and 5 are shown as an example of these profiles. It should be noted that the application of Eq. (8) is limited to experimental work since it is derived from a series of laboratory experiments. For those flow profiles that have been dimensionless in each weir, curves with the overall shape of Eq. (8) from the data have been fitted.

To derive the effects of changing upstream side slopes on the water surface profiles, Eq. (8) was expressed in its original parameters as:

Table 3. Constant Coefficients of Eq. (8) in various Weirs

Upstream side slope	R^2	a	b	c
90º	0.992	0.733	0.269	0.646
60º	0.980	0.769	0.255	0.638
45º	0.977	0.770	0.242	0.638
30º	0.976	0.783	0.222	0.597
15º	0.972	0.782	0.259	0.789

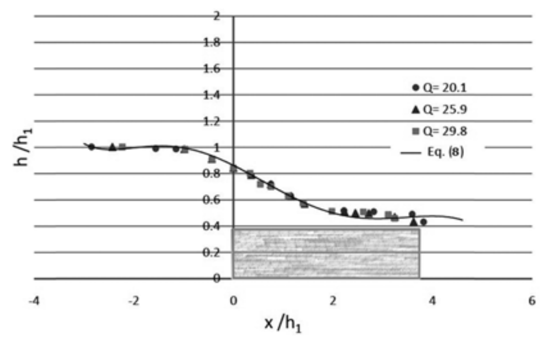

Fig. 4. Fitted Flow Profile over the Weir with Upstream Side Slope of 90 Degree

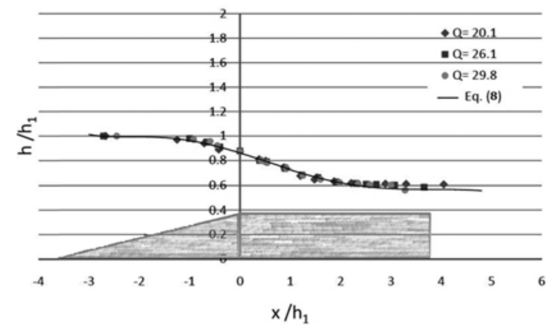

Fig. 5. Fitted fLow Profile over the Weir with Upstream Side Slope of 30 Degree

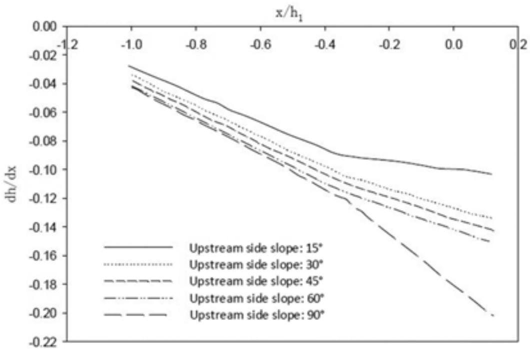

Fig. 6. Slope of Water Surface Profiles (water surface profiles slope in Q = 25 (l s^{-1}))

$$\frac{h}{h_1} = a - b\left[\tanh\left(\frac{x}{h_1} - c\right)\right] \tag{9}$$

and its derivative was then computed as:

$$\frac{dh}{dx} = -b\left[1 - \tanh^2\left(\frac{x}{h_1} - c\right)\right] \tag{10}$$

Equation (10) was then sketched for all weirs using all measured data and the results showed that reducing the upstream side slopes results in a declining flow profile slope accordingly (Fig. 6).

4.3 Checking the Negative Velocity

The velocity values along the flow direction increase and flow passes from sub-critical to the super-critical condition. In addition, flow velocity tends to be zero at the standard weir's entrance edge and higher than zero at the entrance edge of weirs with upstream sloped sides, reflecting an easy flow pass through the weir crest. Furthermore, return currents which occurred at the weir's edge and with flow velocity becoming negative was diminishing by reduced upstream side slopes. No negative velocity was observed for weir with upstream side slope of 30 (Fig. 7).

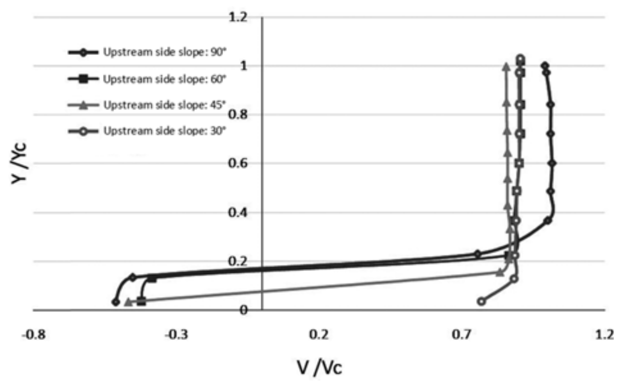

Fig. 7. Sections with Negative Velocity over the Weir Crest Edge

5. Conclusions

In this study, a series of laboratory experiments were conducted to investigate the effect of changing upstream slope of rectangular broad-crested weirs on discharge coefficient, velocity profile, and the flow separation zone. By analyzing experimental results, the following conclusions can be drawn:

1. The weir discharge coefficient value at a 15 slope is about 19.17% higher than for a weir with a 90 upstream side slope. Furthermore, the experimental data illustrated that the new correction factor C_r presented reasonable results to estimate the discharge coefficient of rectangular broad-crested weirs with different upstream side slopes in order to more useful design.
2. Reduce upstream side slopes resulted in decreased approaching flow curvature and water profiles were closing to a horizontal streamline over the weir crest. The proposed hyperbolic equation with different coefficients and constant values for each weir was shown to be reliable for the flow profiles in this study.
3. No negative velocity was observed in weirs with upstream slopes of less than 45 that has a considerable effect on the flow pattern.

Notations

a, b, c = Constant coefficients
A_u = Useful cross section (m^2)
B = Width of weir (m)
C_d = Discharge coefficient of the weir (–)
C_r = Correction coefficient (–)
g = Acceleration of gravity (m s^{-2})
H = Dimensionless parameter
h = Overflow head over the crest (m)
h_1 = Overflow head upstream of the weir (m)
h_{max} = Depth at upstream before the drop in water level (m)
L = Weir length (m)
L_r = Rectangular length (m)
L_w = Wedge Length (m)
V = Flow velocity (m s^{-1})
V_c = Flow velocity at critical section (m s^{-1})
P = H
Q_a = Actual discharge (m^3 s^{-1})

Q_t = Theoretical discharge ($m^3 s^{-1}$)
Y = Height from crest weir (m)
Y_c = Height of the critical section (m)
x = Distance from beginning of crest (m)
X = Dimensionless parameter
α = Upstream side slope of rectangular broad-crested weir
ξ = Dimensionless parameter (ξ = (h-P)/L)

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