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The effect of crest shape on discharge coefficient at linear weirs

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Professional paper

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The effect of crest shape on discharge coefficient at linear weirs

A detailed experimental laboratory analysis of the effect of crest shape on the discharge coefficient of sharp-crested weirs is presented in the paper. The experiments were conducted for four different crest shapes. The experiments and analyses show that discharge capacity, and discharge coefficient in particular, are significantly affected by weir crest height. It is stated in conclusion that rounded crest shape has the highest discharge capacity. In practice, sharp crested weirs are generally preferred to other crest shapes due to construction facility, although the discharge coefficient values of sharp crested weirs are lower compared to rounded crest shape.

Key words:
crest shape, discharge capacity, discharge coefficient, open channel flow, weir

Stručni rad

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Utjecaj oblika krune na koeficijent prelijevanja linearnih preljeva

U radu se daje detaljan prikaz eksperimentalne laboratorijske analize utjecaja oblika krune na koeficijent prelijevanja oštrobridnih preljeva. Eksperimenti su provedeni za četiri različita oblika krune. Obavljeni eksperimenti i analize pokazuju da visina krune preljeva vrlo značajno utječe na brzinu otjecanja, a naročito na koeficijent prelijevanja. U zaključku se navodi da se najveća brzina protoka ostvaruje pri jednočetvrtinskom zaobljenju krune. U praksi se prednost daje izvođenju oštrobridnih preljeva zbog jednostavnosti izvođenja, iako je njihov koeficijent prelijevanja niži u usporedbi s preljevima s jednočetvrtinskim zaobljenjem krune.

Ključne riječi:
oblik krune, kapacitet prelijevanja, koeficijent protoka, strujanje u otvorenom vodotoku, preljev

1. Introduction

Weirs rank among the oldest flow-measurement structures. The hydraulic structures placed horizontally to the canal axis, and allowing water to flow over them, are called weirs. These hydraulic structures are used in irrigation, and in storm water and wastewater systems. Additionally, weirs are used in the process of oxygen transfer and water aeration.

Generally, weirs can be grouped into thin-edged weirs (i.e. sharp-crested weirs), thick-edged weirs, and labyrinth weirs. Thin-edged weirs can be rectangular, triangular, trapezoidal and half-circular. There are also special types of weirs such as Sutro Weirs [1]. Similarly, there are many types of thick-edged weirs. Furthermore, weirs may be either contracted or suppressed. Weirs can assume different crest shapes. In contracted weirs, there is an equal narrowing at both sides of the canal. Both types, contracted weirs and suppressed weirs, are used in hydraulic and environmental engineering. It should be noted that hydraulic characteristics of flow are greatly influenced by the type and shape of weirs. The cross-sectional views of a rectangular suppressed weir are presented in Figure 1. Equation (1) is commonly used for suppressed weirs in hydraulic engineering. This equation is known as Poleni equation.

$$Q = \frac{2}{3} \times C_d \times H_1^{3/2} \times \sqrt{2g} \times L \tag{1}$$

where Q is the discharge (m³/s), C_d is the discharge coefficient (-), H_1 is the total load on crest (m), g is the gravitational acceleration (m/s²), L is the length of crest (m). The total head, H_1, given in Eq. (1)

$$H_1 = h + \frac{V_1^2}{2g} \tag{2}$$

where:

h - is the nappe height on the upstream of the weir [m]

V_1 - is the flow velocity [m/s].

Weirs can be installed horizontally to the direction of flow, and they can be shaped in form of a broken line and circular, and also at an angle with the direction of flow [2]. The shape of crest is one of important parameters that effect the discharge capacity. In his master's degree thesis on the design performance of labyrinth weirs, Amanian [3] states that the height, thickness, and shape of weirs have an important effect on the discharge coefficient. Waldron emphasises the importance of this issue in his master's degree thesis [4] and makes several experiments on labyrinth weirs.

A lot of experiments are conducted in this study to determine the effect of crest shape on the discharge coefficient in suppressed weirs. The weir shapes used in the current study are sharp-crested, ½ rounded, ¼ rounded and straight crested. Therefore, as weirs are used in several areas of hydraulic and environmental engineering, the study on weirs of different crest shapes – involving discharge coefficients and hydraulic characteristics - will fill the gap in this field of study.

2. Sharp-crested weirs

There are several types of sharp-crested weirs (Figure 2). The 90° sharp-crested triangular weirs are most widely used for discharge calculations. In literature, there are many discharge coefficient formulae concerning sharp-crested weirs. The most extensive study in this field was conducted by Kindsvater and Carter [5]. In this the equation, the width of the weir and the height of water on the weir, are used by making a correction. The researchers proposed a discharge coefficient depending on b/B and h/P, where b is the crest width (m), B is the channel width (m), and P is the crest height (m).

For rectangular contracted weirs, Francis proposed Eq. (3) in 1883 (USBR 2001),:

$$Q = 1.83\,(L-0.2h)h^{3/2} \tag{3}$$

For suppressed weirs with $\frac{P}{H_1} < 5$ Rehbock [6] proposed Eq. (4).

$$C_d = 0,611 + 0,08\frac{H_1}{P} \tag{4}$$

For suppressed weirs with $\frac{P}{H_1} > 20$ Henderson [7] proposed Eq. (5).

$$C_d = 1,06\left(1 + \frac{P}{H_1}\right)^{3/2} \tag{5}$$

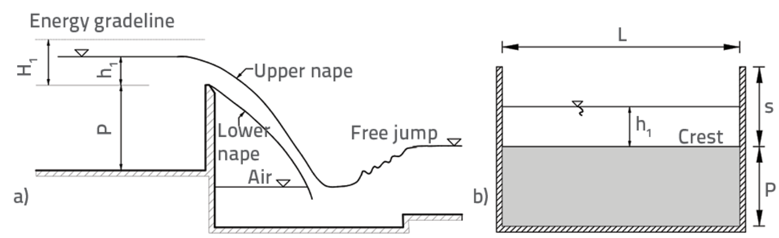

Figure 1. Rectangular suppressed weir: a) Longitudinal section; b) Cross-section

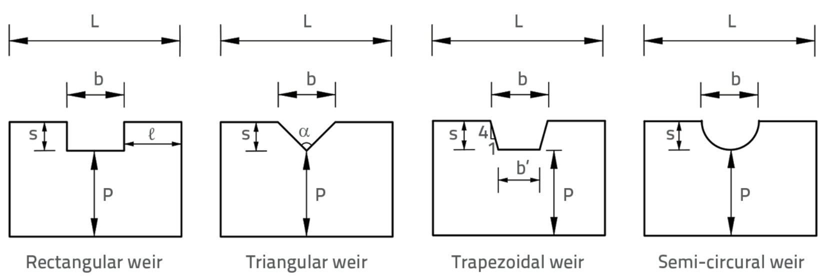

Figure 2. Sharp-crested weirs

Sisman et. al. [8] investigated discharge measurements for sharp-crested and rectangular cross-section weirs. In this context, they carried out a series of experiments ranging from full opening of the weir to narrow opening of the weir. They proposed Eq. (6) to compute the discharge over both the full opening and narrow opening weirs.

$$Q=\left[-0.001+0.254\left(\frac{b}{L}\right)+0.366\left(\frac{b}{L}\right)^2-1.631\left(\frac{b}{L}\right)^3\right]h_1 + \left[0.015+3.212\left(\frac{b}{L}\right)-8.068\left(\frac{b}{L}\right)^2+39.609\left(\frac{b}{L}\right)^3\right]h_1^2 \tag{6}$$

Researchers reported that the discharge coefficient is dependent on the following dimensionless parameters for contracted weirs Eq. (7).

$$C_d=f\left(\mathrm{Re},We,\frac{h_1}{b},\frac{b}{L},\frac{h_1}{P}\right) \tag{7}$$

where
Re - is the Reynolds number
We - is the Weber number
h_1 - is the flow depth [m].
Other symbols are shown in figures 1 and 2.

Tokyay and Turhan [9] conducted an experimental study aimed at defining the discharge coefficient on sharp-crested weirs. They conducted this study for the $5<H_1/P<20$ interval so as to obtain the equation that gives the discharge coefficient in suppressed weirs. The equation is dependent upon H_1/P. The researchers stated that the unit discharge on weir is q, and that the mass density of fluid is ρ, the dynamic viscosity is μ, the surface tension is σ and the gravity due to acceleration is g Eq. (8).

$$q=f_1(P,H_1,\rho,\mu,\sigma,g) \tag{8}$$

Equation (9) is derived from Eq. (8).

$$\frac{q}{h_1\sqrt{gh_1}}=f_2\left(\frac{P}{H_1},\mathrm{Re},\ We\right) \tag{9}$$

according to which the coefficient is calculated C_d, Eq. (10):

$$C_d=f_3\left(\frac{P}{H_1},\mathrm{Re},\ We\right) \tag{10}$$

Generally, in the fluid mechanics, when the Reynolds number increases the flow is independent from that number. The Weber number becomes important in the situations when the nappe height is small [9]. Tullis et al. [10] proposed the Eq. (11) for discharge coefficient of suppressed weirs with the ¼ rounded crest.

$$C_d=0.49+1.46(H_1/P)-2.56(H_1/P)^2+1.44(H_1/P)^3 \tag{11}$$

The researchers stated that this equation is valid for $H_1/P<0.7$. The Eq. (12) is used for sharp-crested suppressed weirs [11]. This equation is valid for some situations such as: $P>0.06$ m, $h_1>0.01$ m and $h_1<0.8\,P$.

$$C_d=0.605+\frac{1}{1000h_1}+0.08\frac{h_1}{P} \tag{12}$$

For the measurement of low flows, the use of triangular weirs gives more accurate results when compared to other weir shapes. The apex angle of the triangular weir is generally taken to be 90°. If the discharge is very small, then a small apex angle can be used (e.g., 30°, 45°) for high nappe load.
As mentioned above, triangular sharp-crested weirs are widely used in practice for the measurement of low discharges. Equation (13) is proposed by Gourley and Crimp [12]. It is a commonly used simple formula that offers practical values. For the sharp-crested 90° bedding angled weir $tg(\alpha/2)$ statement is equal to 1, and the formula becomes more simple.

$$Q=1.32\,tg\frac{\alpha}{2}h^{2.47} \tag{13}$$

where α is the apex angle of the sharp-crested triangular weir.

3. Some design criteria for weirs

Some criteria about the design of weirs are given here:

- The head of weir structure should be vertical, sharp and vertical to the channel flow.
- The plane of weir edges can be vertical or angled.
- All weir coating should have the same thickness.
- The nappe should touch only the corners on the crest head surface, it should not stick to the river mouth surface, and free nappe should be preserved.
- The maximum river mouth water height should be below the height of the crest. For the constitution of free nappe, the elevation difference between the weir crest and the river mouth water level should be at least 6 cm (USBR 2001). French [1] proposed that this distance be 5 cm.
- At the sharp-crested weirs; the nappe height should be 2 cm in laboratory conditions. Coleman and Smith [13] proposed that the nappe height should not be less than 19 mm because of the tension on the weir crest. 7 ≤ h ≤ 60 cm [1] is given for the nappe height. Here h denotes the nappe height. If the nappe height is too small, the discharge coefficient formula should involve the Weber number.
- At the narrow-edge weirs; if the horizontal length of inner section where water flows and the lateral wall is shown with "ℓ", the equation of $\ell \geq 3h$ should be taken into consideration. When the weir is being manufactured, the 5-6 cm section that goes inside the concrete should be taken into consideration at the time of calculation of the metal plaque width and height, [14].
- The nappe height should be calculated using the distance of 3 to $4h_{max}$ from the weir crest, [1]. Here h_{max} represents

the maximum nappe height over the weir. Reports that the measurement of the nappe height from the distance of 2 m should be sufficient. [14],

- The thickness of crest is assessed using structural analysis. In other words, the thickness of wall depends on hydrostatic forces, Ice load, and special conditions prevailing at the place where the weir is placed. For the economy and resistance purposes, the thickness can be increased at the river mouth side. The increase in thickness at the river mouth does not have any effect on the discharge coefficient. The crest thickness on the thin-edged weirs can be taken to be 1/6 of the crest height [15].
- If the weir is going to be used for ventilation or oxygen transfer, the depth of river mouth pool, including the width and height, gains in importance. The maximum depth of air bubbles generated by water jet in the river mouth pool is called the penetration depth. The river mouth pool depth should be bigger than the penetration depth. Additionally, the jet width of the river mouth pool of triangle and maze weirs is open and assumes the shape of a bow. On the other hand, the jet width is small at rectangular weirs. This fact should be taken into account when the river mouth pool width is assessed. Emiroglu [16] provides equations about an optimum scaling of river mouth pools.

4. Experimental setup

Experiments were conducted at the Hydraulic Laboratory of the Department of Civil Engineering, Faculty of Engineering, Firat University. The experimental setup is shown in Figures 3 and 4. The system discharge is operated via the 25 cm main pipe connected to the main reservoir. The water first runs to the chamber measuring 1.00 x 2.80 x 3.60 = 10.08 cubic metres. Trash racks and bricks are placed at the entrance of the reservoir to muffle the energy. After reservoir, water enters the access channel 0.80 m in height and 1 m in width. This channel is 3.0 metres in length. In experiments, the downstream level was applied less than the upstream level in the part where weir was placed. The prepared weirs were positioned at the end of the access channel. Trash racks and bricks were placed as necessary to provide for the steady flow conditions. Experiments were conducted for the conditions of steady flow and free overflow. Level measurements were made using a digital Mitutoyo limnimetre with ±0.01 mm sensitivity. The level measurements to the head were taken to a distance which is 5 times onward to the nappe height. The limnimetre placed above the measurement car is shown in Figure 4. The measurement car can move in the x and y directions near the upstream end of the weir at the channel axis. Velocity measurements were conducted using a Nortec acoustic velocity meter.

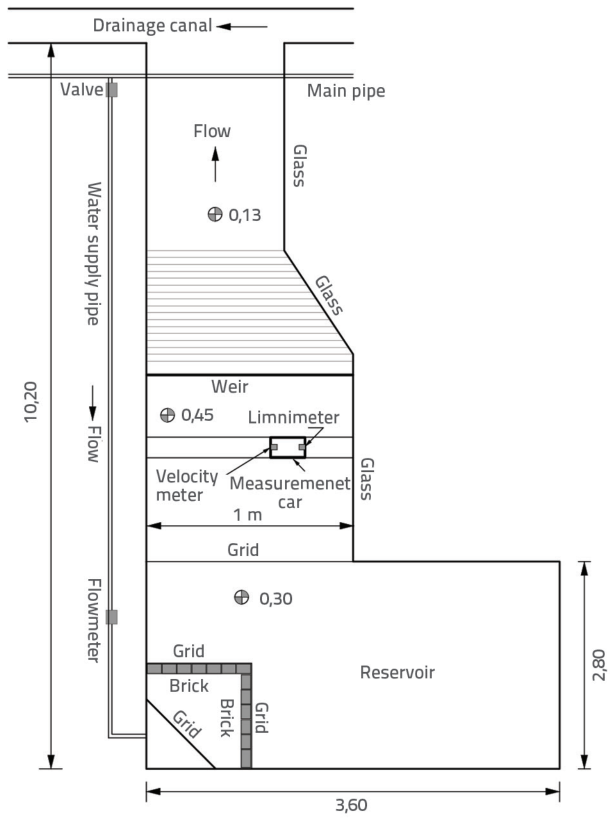

Figure 3. Schematic view of experimental setup

Figure 4. A view from experimental setup [17]

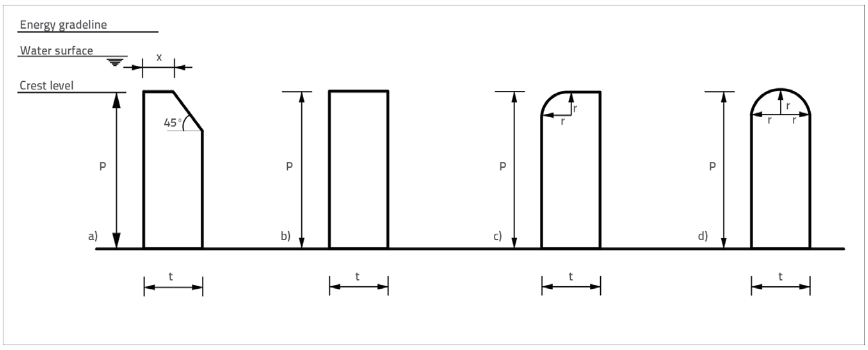

Figure 5. Tested crest shapes

Four different crest shapes are taken into consideration to determine the effect of crest shape on discharge coefficient. These are:
- sharp-crest
- flat top crest
- 1/4 rounded crest
- 1/2 rounded crest (Figure 5).

These weirs were made of wood and painted.
The equations below were used for determining the size of weirs. These equations were suggested by Tullis et al. [10] and are used for labyrinth weirs. They were also used in this study.

$$r = P/12 \tag{15}$$

$$t = P/6 \tag{16}$$

$$x = t - r \tag{17}$$

where
r - is the crest radius of curvature [cm]
t - is the weir thickness [cm]
x - is the straight distance of sharp crested weirs in crest.

In this study, the information about experiment variables is summarized in Table 1. Painted wooden weirs were placed vertically to the stream, and necessary imperviousness was ensured. As can be seen in Table 1, the weir length amounted to 100 cm and crest heights were 10, 15, 20 cm.
The weir 10 cm in height was first placed into the set and the experiments were conducted by increasing the height of the nappe, starting from 25 mm to 100 mm. This procedure was implemented by increasing the nappe height in 5 mm increments. Coleman and Smith [13] suggested that 19 mm minimum thickness of nappe should be adopted because of the surface tension on crests. The Weber number can therefore be ignored. Novak and Cabelka [18] proposed a minimum nappe height of 30 mm to minimize the surface tension effect. Thus, the minimum nappe height was taken to be 30 mm in this study.
In this weir, the discharge varies from approximately 8.5 to 80 L/s. The experiments were carried out under the same conditions for all tested weirs 10 cm in height. The maximum nappe height amounted to 150 mm for experiment series whose weir heights were 15 and 20 cm. The discharge amounted to approximately 8.5 to 150 L/s for experiment series whose weir heights were 15 and 20 cm.
After adjusting selected nappe heights with digital limnimetre, the valve was opened and the water was introduced into the system. Sufficient time was allowed to obtain the desired nappe height value using the valve conveying water to the experimental setup. The flow for this nappe height was recorded by a Siemens electromagnetic flowmeter at the main pipe line. Then, an average velocity of flow was measured by the ADV velocity meter. All experiment series were carried out according to this procedure.

Table 1. Experiment variables

Variable (1)	**Value (2)**
Crest length, L [cm]	100
Crest height, P [cm]	10. 15. 20
Weir thickness, t [cm]	1.67; 2.50; 3.33
Crest radius of curvature, r [cm]	0.83; 1.25; 1.67
Distance in crest on sharp-crested weir, x [cm]	0.84; 1.25; 1.66
Discharge, Q (L/s)	8.71-136.34
Flow depth, h_1 [cm]	2.23-15.00
Odnos H_1/P. [-]	0.15-1.12
Kinetic energy rectification factor, α	1.0
Experimental runs	192

5. Experimental results and discussion

A chart based on experimental data, shown in Table 2, is presented in order to determine the effect of crest shape on the discharge. The nappe height was measured by digital limnimetre with millimetre identity. However, the discharge was taken into consideration as m^3/s while calculating the discharge coefficient by Eq. (4) with necessary identity exchanges. The changes of H_1/P with C_d are shown in Figures 6 to 9. The discharge coefficient is a function of the Reynolds number, Weber number and H_1/P. The Reynolds number and Weber number, stated by Tokyay and Turhan [15], were ignored because of the above stated reasons. Therefore, the discharge coefficient is only the function of H_1/P. For this reason, graphs were drawn between H_1/P and C_d.
It can be seen in Table 2 that while there is an increase in nappe height, there is a decrease in discharge coefficient. The graph showing the calculated discharge coefficient and H_1/P is given in Figure 6. It can be observed that the matching trend line is a third degree polynomial. It can also be observed that the discharge

Table 2. One quarter rounded Crest (*P/L* = 15/100 = 0,15; *t* = 2,50; *r* = 1,25)

h_1 [cm]	V_1 [cm/s]	Q [L/s]	$V_1^2/2g$ [cm]	H_1 [cm]	C_d [-]	h_1/P [-]	H_1/P [-]
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
2.5	5.91	9.27	0.017802	2.517802	0.785758	0.166667	0.167853
3.0	6.91	12.88	0.024336	3.024336	0.777777	0.200000	0.201622
3.5	7.91	15.22	0.031890	3.531890	0.776508	0.233333	0.235459
4.0	8.91	18.91	0.040463	4.040463	0.788473	0.266667	0.269364
4.5	9.91	21.91	0.050055	4.550055	0.764468	0.300000	0.303337
5.0	12.16	26.66	0.075365	5.075365	0.789589	0.333333	0.338358
5.5	14.4	30.03	0.105688	5.605688	0.766220	0.366667	0.373713
6.0	16.65	35.20	0.141296	6.141296	0.783239	0.400000	0.40942
6.5	19.56	40.31	0.195002	6.695002	0.788004	0.433333	0.446333
7.0	22.46	46.60	0.257111	7.257111	0.807202	0.466667	0.483807
7.5	25.37	51.50	0.328051	7.828051	0.796285	0.500000	0.52187
8.0	27.12	55.36	0.374870	8.374870	0.773519	0.533333	0.558325
8.5	28.85	60.97	0.424221	8.924221	0.774466	0.566667	0.594948
9.0	30.61	66.40	0.477560	9.477560	0.770664	0.600000	0.631837
10.0	35.42	78.11	0.639438	10.63944	0.762203	0.666667	0.709296
11.0	40.23	88.99	0.824900	11.82490	0.741117	0.733333	0.788327
12.0	45.05	103.40	1.034405	13.03440	0.744090	0.800000	0.86896
13.0	49.86	114.40	1.267084	14.26708	0.718894	0.866667	0.951139
14.0	54.67	129.01	1.523348	15.52335	0.714311	0.933333	1.03489
14.5	57.08	132.20	1.660615	16.16061	0.689107	0.966667	1.077374

coefficient decreases with an increase in H_1/P. Many other researchers have also established that the discharge decreases with an increase in nappe height (Tullis et al. [10]; Kumcu. [18]).

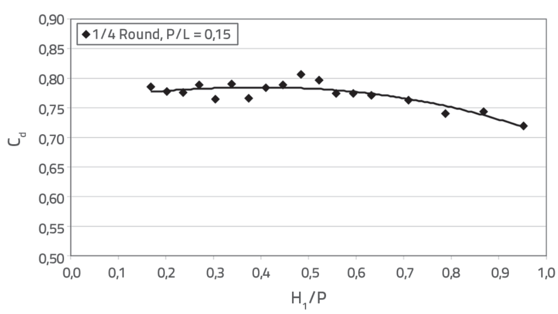

Figure 6. *P/L* = 15/100 = 0.15 and C_d and H_1/P change for ¼ rounded crest shape

Figure 7.a to 7.c shows a decrease with an increase in H_1/P. When four different crest shapes are examined, it can be seen that the 1/4 rounded crest shape has greater discharge coefficient values. Similar results are also seen in 1/4 and 1/2 rounded weirs for lower H_1/P values. Straight weirs have a lower discharge coefficient. It can be observed that discharge coefficient values of sharp-crested and straight-crested weirs are nearly similar in the H_1/P is range greater than 0.50.

Figure 8.a to 8.d was plotted so as to see the effect of crest height on discharge coefficient for different crest shapes. Figure 8.a was drawn between C_d and H_1/P for the 1/4 rounded crest

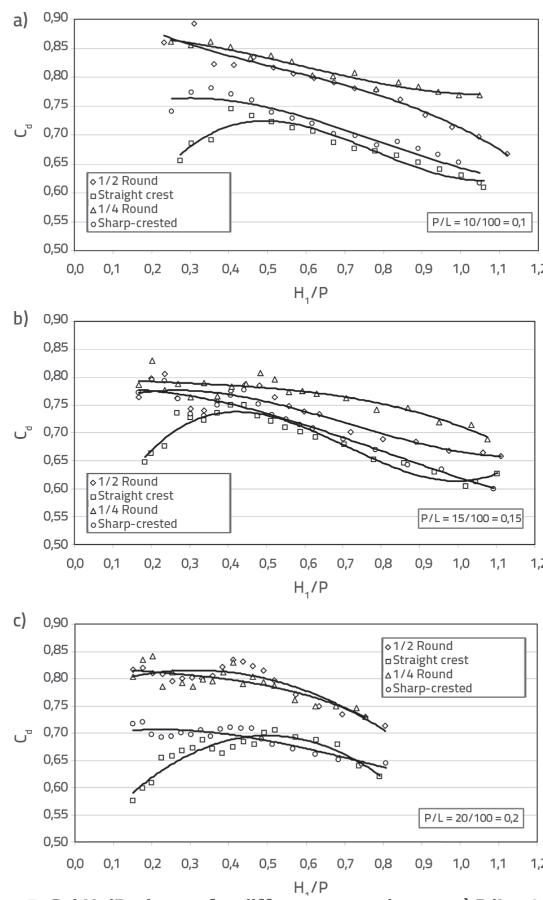

Figure 7. C_d i H_1/P change for different crest shapes: a) P/L = 0.10; b) P/L = 0.15; c) P/L = 0.20

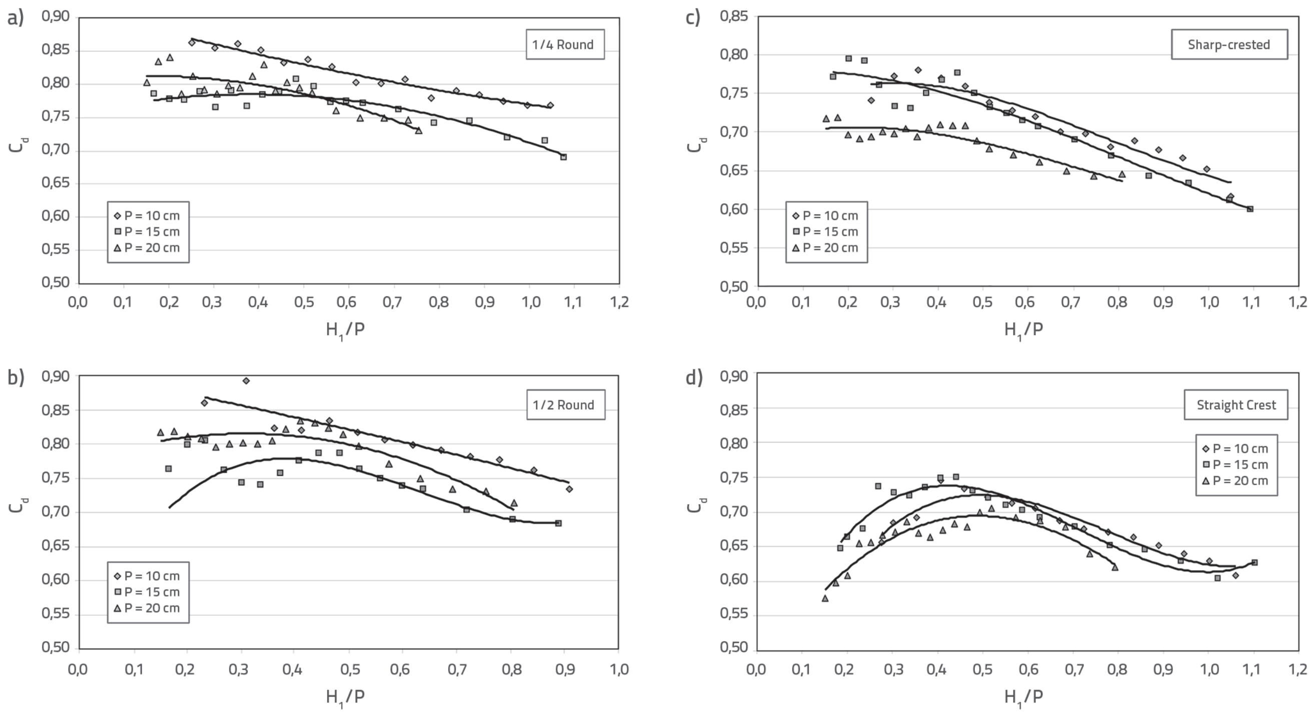

Figure 8. Change of H_1/P and C_d with crest height: a) 1/4 rounded crest; b) 1/2 rounded crest; c) sharp crest; d) straight crest

shape. As shown in the stated figure, increases in crest height generally cause decreases in discharge coefficient. This situation was also noted in other tested crest shapes (Figure 8.b to 8.d).

Table 3. Comparison of ¼ rounded crest shapes with different weir heights

P/L	Straight crest [%]	Sharp-crest [%]	½ rounded crest [%]
0.10	16.34	12.47	2.82
0.15	10.17	6.68	3.95
0.20	16.21	12.72	0.56

1/4 rounded weirs with bigger discharge coefficient are compared with other weirs in Table 3. Percent values in Table 3 were calculated based on this statement: "(discharge coefficient of 1/4 rounded crest shaped weirs - discharge coefficient of straight crest shaped weirs) / (1/4 rounded crest shaped weirs). Here, it can be observed for P/L=0.10 that approximately 16.34 % of water passes through for straight crest shaped weirs, 3.12 % for 1/2 rounded, and 12.47 % for sharp edged weirs. For P/L = 0.15, it can be observed that 10.17 % of water passes through for straight weirs, 3.95 % for 1/2 rounded weirs, and more than 6.68 % for sharp edged weirs.

For P/L = 0.20, approximately 10.17 % of water passes through for straight weirs, and more than 12.72 % for sharp-crested weirs, while less than 0.56 % of water passes through for ½ rounded weirs.

The Statistica software was used to obtain the discharge coefficient equation of suppressed linear weirs with different crest shapes, cf. Eq. (1). While obtaining equations in this study, all experimental data were used for 10, 15 and 20 cm. The obtained equations are given below. It can be noted that these equations are valid for $H_1/P < 1$.

$$C_d = 0{,}363+2{,}047\,(H_1/P)-4{,}015\,(H_1/P)^2+3{,}031\,(H_1/P)^3-0{,}802\,(H_1/P)^4 \quad (18)$$

$$C_d = 0{,}701+0{,}198\,(H_1/P)-0{,}044\,(H_1/P)^2-0{,}658\,(H_1/P)^3+0{,}439\,(H_1/P)^4 \quad (19)$$

$$C_d = 0{,}763+0{,}324\,(H_1/P)-0{,}667\,(H_1/P)^2+0{,}255\,(H_1/P)^3+0{,}012\,(H_1/P)^4 \quad (20)$$

$$C_d = 0{,}772+0{,}227\,(H_1/P)-0{,}560\,(H_1/P)^2+0{,}338\,(H_1/P)^3-0{,}067\,(H_1/P)^4 \quad (21)$$

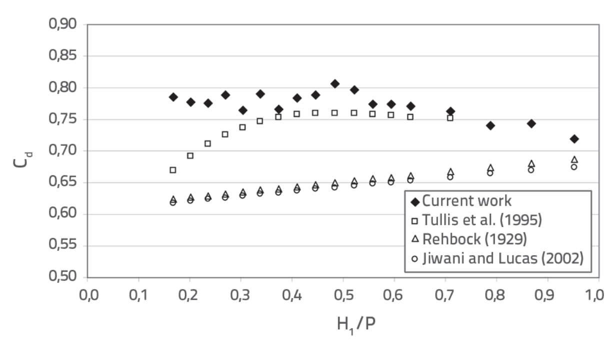

Figure 9. Comparison of current data from our study with Tullis et al. [10], Rehbock [9] and Jiwani i Lucas [11]

Equation (18) is related to straight crests, equation (19) concerns sharp-edged crests, equation (20) is for 1/2 rounded crests, and equation (21) is related to 1/4 rounded crests. The correlation coefficients of these equations are 0.74, 0.81, 0.84 and 0.87, respectively.

6. Conclusions

A considerable number of experimental runs were conducted in this study to determine the discharge coefficient of suppressed linear weirs having different crest shapes. The findings obtained are summarized as follows:

- It can be seen that crest shape of the weir is an important parameter that affects the discharge coefficient or discharge capacity.
- It can also be seen that the discharge coefficient decreases with an increase in weir height, for all the weir types.
- It can be observed that the discharge coefficient decreases with an increase in H_1/P values, for all weirs tested.
- It can be seen that linear weirs with the 1/4 rounded crest have greater discharge coefficient values compared to other tested weirs crest shapes.
- It can be concluded that the straight shaped weir has the lowest discharge coefficient.
- If the tested weir types are ordered according to discharge coefficient, the following order of precedence can generally be adopted: 1/4 rounded, 1/2 rounded, sharp-crested, and straight crested weirs.
- The equations revealing the discharge coefficient for each crest shape were obtained based on measured data.

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