MODULAR FLOW OF SMALL DISCHARGES OVER WEIRS WITH VERTICAL FACES

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Summary: *The international standard ISO 3846:2008 is intended for determining water discharge Q for overflow heads higher than h_1=0.06 m, over rectangular, full-width, sharp edge weirs having vertical upstream and downstream faces. The subject of this paper is modular flow at h_1<0.06 m. The flow in this domain might be influenced by viscosity and surface tension. Two approaches are present in the expert literature regarding determination of flow: a) this flow domain influenced by viscosity and surface tension is completely excluded of analysis, or b) the mentioned influences are neglected in determination of the Q-h_1 relationship. Weirs of crest lengths of 0.095, 0.19 and 0.5 m have been examined in the hydraulic laboratory of the Faculty of Civil Engineering in Subotica (Serbia) between 28th of December 2018 and 20th of February 2019. This paper complements the international standard for determining the Q-h_1 relationship at h_1<0.06 m.*

Keywords: *crest without ramps, sharp edged weir, modular flow, viscosity and surface tension of water*

1. INTRODUCTION

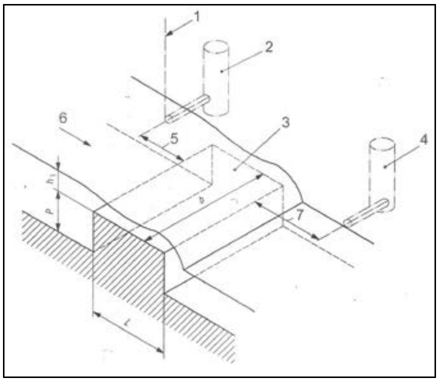

Figure 1 Modular flow over a broad-crested, sharp edged weir without upstream and downstream ramps [1]

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Modular flow over full-width, sharp edged weir of vertical upstream and downstream faces is examined (Figure 1). The flow height-discharge relationship is categorized as follows:

- flow over a long-crested weir ($0<h_1/L\leq0.1$) [2-4],
- flow over a broad-crested weir ($0.1\leq h_1/L\leq0.4$) [1-4],
- flow over a short-crested weir ($0.4\leq h_1/L\leq1.5$-2) [1-4] and
- flow over a sharp crested weir (1.5-$2\leq h_1/L$) [2, 4].

Modular flow over a broad-crested weir in the Republic of Serbia is calculated using the following equation:

$$Q=mb\sqrt{2g}h_1^{3/2} \quad (1)$$

where *m* is the discharge coefficient, *b* is the width of the weir and *g* is the gravity acceleration (Figure 1). In general, the discharge coefficient of broad-crested weir depends on h_1/P, h_1/L, h_1/b, *We* and *Re*, where *P* and *L* are the height and length of the weir, $Re=g^{1/2}h_1^{3/2}/\nu$ is the Reynolds number, $We=\rho g h_1^2/\sigma$ is the Weber number, ν is the kinematic viscosity, ρ is density, and σ is the coefficient of water surface tension [5-7].

1.1 The maximum flow head h_1 influenced by viscosity and water surface tension

According to the international standard, the discharge coefficient in equation (1) is:

$$m=2C/3^{3/2} \quad (2)$$

Coefficient *C* depends on h_1/L and h_1/P (Figure 2).

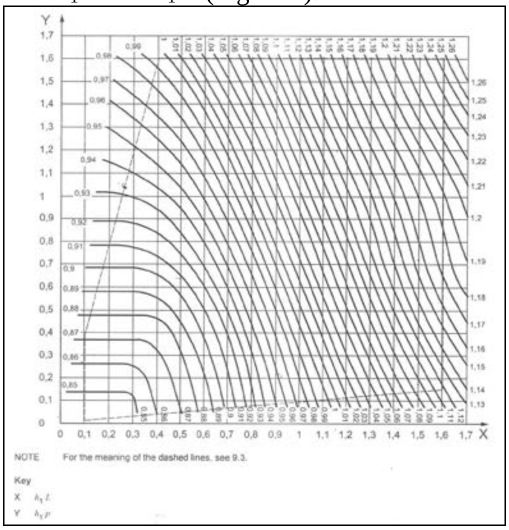

Figure 2 Chart for the determining coefficient C with the limits of validity (dashed lines) [1]

The dashed lines in Figure 2 represent the limits imposed by the following restrictions:

a) to avoid viscosity and surface tension effects: $h_1 \geq 0.06$ m, $b \geq 0.3$ m, $P \geq 0.15$ m,

b) there are no calibration data available beyond the practical limits: $0.1<L/P<4$, $0.1<h_1/L<1.6$, and

c) to avoid unstable water levels: $h_1/P<1.6$.

Based on the h_1/L values it may be concluded that the standard applies to the cases of broad-crested and short-crested weirs without the influence of viscosity and water surface tension on flow.

In order to avoid the influence of fluid properties, boundary roughness, and the accuracy with which h_1 can be determined, Bos (1989) recommends flow heads $h_1 \geq (0.06$ m and $0.08L)$ [8].

Hager and Schwalt (1994) performed experiments with water of temperature 15°C [9]. They have analyzed the value of discharge coefficient in function of flow head for long-crested and broad-crested weirs (Figure 3).

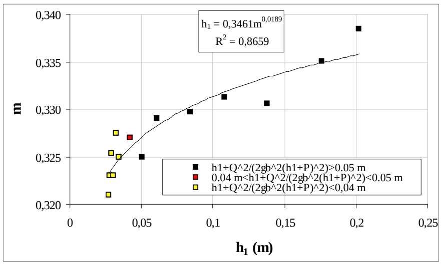

Figure 3 Discharge coefficient in function of flow head in test series by Hager and Schwalt (1994)

Flow head varied from 0.027 m to 0.2021 m (Table 1).

BS ISO 3846:2008	$h_1 \geq 0.06$ m	$b \geq 0.3$ m	$P \geq 0.15$ m	L (m)	$0.1<L/P<4$	$0.1<h_1/L<1.6$	$h_1/P<1.6$
Bazin, 1896 [3]	*0.055-* 0.447 m	2 m	0.75 m	0.1-2 m	0.133-2.667	*0.03*-1.93	0.073-0.596
U.S. Geological Survey, 1903 [3]	*0.023-* 1.35 m	4.87 m	3.43 m	0.146-5 m	0.042-1.458	*0.005-4.15*	0.007-0.396
Keutner, 1934 [3]	*0.0355-* 0.26 m	*0.1 m*	0.5 m	0.1-2 m	0.2-4	*0.035-2.21*	0.071-0.52
Prentice, 1935 [7]	*0.030-* 0.183 m	0.3 m	0.2 m	0.61-0.91 m	3.05-*4.55*		0.15-0.915
Washington, 1941 [3]	*0.016-* 0.097 m	*0.254 m*	*0.08-0.14 m*	0.34 m	2.429-*4.25*	*0.047*-0.29	
Minnesota, 1941 [3]	*0.021-* 0.173 m	0.512 m	0.1615 m	0.686 m	*4.248*	*0.03*-0.251	0.13-1.071
Tison, 1950 [7]	*0.044-* 0.165 m	0.5 m	0.3 m	1.8 m	*6*	*0.024-0.092*	0.147-0.55
Berezinskij, 1950 [7]	*0.045-* 0.358 m	0.51-1.92 m	*0.03-* 0.46 m	0.39-2.5 m			

Govinda Rao and Muralidhar, 1963 [7]	*0.031*-0.277 m	0.61 m	0.30-0.31 m	0.1-3.05 m			
Wakhlu, 1963 [3]	*0.012*-0.083 m	*0.2032 m*	*0.0508 m*	0.3048 m	*6*	*0.04*-0.273	0.236-*1.634*
Moss, 1972 [7]	*0.033*-0.076 m	0.61 m	0.152 m	0.15-0.76 m	0.987-*5*		0.217-0.5
Sreetharan, 1983 [7]	*0.037*-0.29 m	*0.27*-0.51 m	*0.08*-0.2 m	0.08-0.9 m			
Tim, 1986 [7]	*0.025*-0.122 m	*0.25 m*	*0.1 m*	0.31 m	3.1	*0.081*-0.394	0.25-1.22
Ramamurty et al. 1988 [3]	*0.026*-0.123 m	*0.254 m*	*0.1016 m*	0.3048 m	3	*0.087*-0.4	0.256-1.211
Hager and Schwalt (1994) [9]	*0.027*-0.205 m	0.499 m	0.401 m	0.5 m	1.25	*0.054*-0.41	0.067-0.511
Johnson 2000 [3]	*0.015*-0.787 m	0.923 m	*0.1*-0.15 m	0.038-0.203 m		*0.045-6.3*	
Zachoval et al., 2012 [7]	*0.036*-0.191 m	1 m	0.25 m	0.5 m	2	*0.072*-0.382	0.144-0.764
Bijankhan et al. (2013) [4]	*0.0124*-0.0717 m	0.6 m	*0.1 m* and 0.2 m	0.002-0.2 m	0.02-2.82	*0.063-29.95*	0.063-0.717

Table 1 Overview of the characteristics of the tested flow-height relationships with flow heads $h_1<0.06$ m, and the limits of validity of the international standard

The avoid scale effects the following restriction was imposed: $h_1+Q^2/[2gb^2(h_1+P)^2]\geq 0.04$-0.05 m. According to Figure 3, the above mentioned limitation corresponds to flow heads $h_1\geq 0.05$ m.

The limit in flow head of a weir in terms of viscosity and water surface tension has been investigated by Zachoval et al. (2014) in function of relative error $\delta=\Delta C_d/C_d$, where $C_d=C/(H_1/h_1)^{3/2}$ and $H_1=h_1+Q^2/[2gb^2(h_1+P)^2]$ (Figure 4) [7].

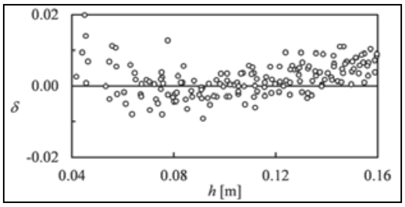

Figure 4 Relative error δ in function of flow head $h=h_1$ based on tests by Zachoval et al. (2014) [7]

Based on Figure 4, the authors have concluded that these influences were negligible for $h_1\geq 0.06$ m, and according to Figure 5 this conclusion applied to broad-crested weirs just in a limited range: $0.12\leq h_1/L\leq 0.3$.

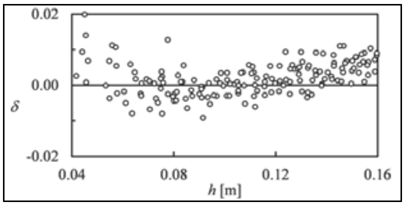

Figure 5 Relative error δ in the function of the relative head $h/t=h_1/L$ based on experiments by Zachoval et al. (2014) [7]

The same authors have concluded that the limit heads declared by Bos (1989) and Hager and Schwalt (1994) represent the limits in terms of the influence of viscosity and water surface tension.
Therefore, equation (2) does not apply to discharge coefficients for flow heads $h_1<0.06$ m.

1.2 Investigation of head-discharge relationship for $h_1<0.06$ m

Following the publication of the international standard, Azimi and Rajaratnam (2009) analyzed the results of measurements obtained in 2000 (Table 1) [3]. They have established new functions for coefficient *C* in equation (2) (Figure 6).

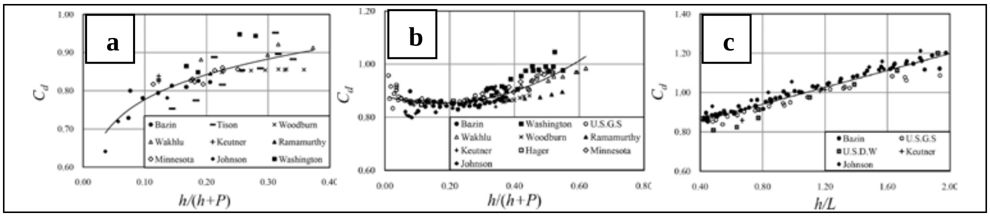

Figure 6 Functions of coefficient $C_d=C$ in equation (2) for long-crested (a), for broad-crested (b) and short-crested weirs (c), where $h=h_1$ [3]

The measurements shown in Figure 6 included flow heads even lower than 0.06 m, except for the measurements performed by Woodburn (1932) and U.S.D.W. (1903). Not all measurements met the requirements of the international standard (these values are written in italic in Table 1). Using coefficients $a_1=1.02$, $b_1=0.12$, $a_2=0.873$, $b_2=-0.3$, $c_2=0.878$, $a_3=0.767$ and $b_3=0.215$, the following types of functions have been determined:

long-crested weirs: $C=a_1[h_1/(h_1+P)]b_1$ (3a)

broad-crested weirs: $C=a_2[h_1/(h_1+P)]^2+b_2[h_1/(h_1+P)]+c_2$ (3b)

short-crested weirs: $C=a_3+b_3(h_1/L)$ (3c)

The above functions do not include parameters standing for viscosity and water surface tension.

At the hydraulic laboratory of the irrigation and reclamation engineering department, University of Tehran, Bijankhan et al. (2013) investigated weirs of flow heads ranging from 0.0124 m to 0.0717 m (Table 1) [4]. The flow height of the examined cases did not always satisfied the requirements of the international standard. The Q-h_1 relationship was determined by neglecting the influence of viscosity and water surface tension. These relationships are presented in two ways. The first type of relation was obtained using the following form:

$$\frac{h_1}{P}=1.5128\left(\frac{K_s}{P}\right)^{1.0328} \tag{4}$$

In equation (4), $Ks=[Q^2/(b^2g)]^{1/3}$. The error in determination of discharge is between ±15% and ±10% (Figure 7).

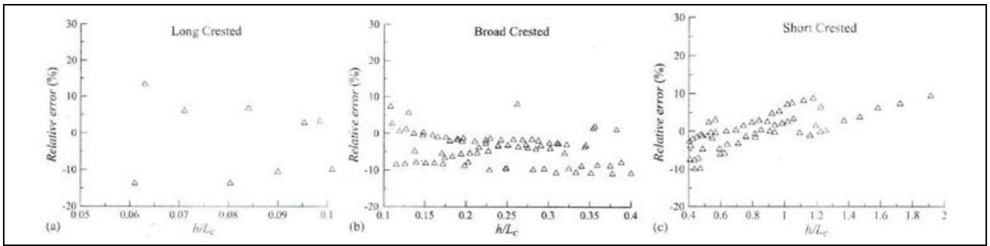

Figure 7 Errors in determining the discharge over the long-crested, broad-crested, and the short-crested weir using equation (4), where $h=h_1$ and $L_c=L$ [4]

The second type of relationship is in form (3). Based on measurements, Bijankhan et al. (2013), have established new coefficients: $a_1=0.532$, $b_1=-0.342$, $a_2=4.2003$, $b_2=-2.5966$, $c_2=1.3563$, $a_3=0.9309$ and $b_3=0.1839$. The margin of error was less than ±10% (Figure 8).

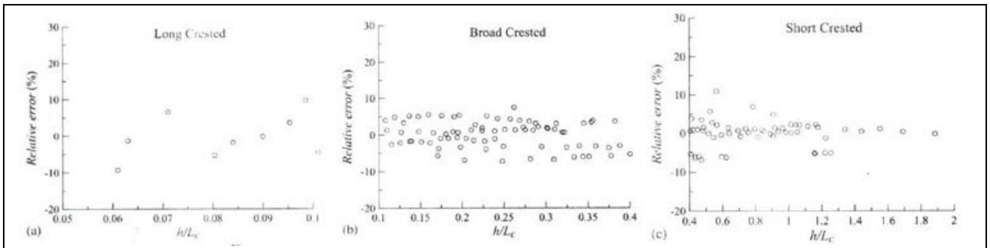

Figure 8 Error in determination of discharge using the test results by Bijankhan et al. (2013) for functions of type (3), where $h=h_1$ and $L_c=L$ [4]

Therefore, in case of weirs, even though required by the international standard, scientific literature ignores the influence of viscosity and water surface tension even for $h_1<0.06$ m. On the basis of the outlined diagrams is evident that in investigations Azimi and Rajaratnam (2009) and Bijankhan et al. (2013), the proposed functions (without the influence of viscosity and water surface tension) are less suitable for long-crested weirs than for broad and short-crested weirs.

In flows with $h_1<0.06$ m a domain of flow exists influenced by viscosity and water surface tension. There is no such function in the aforementioned scientific literature. Based on the results of low flow measurements in case of sharp-crested weir and flume, the following type of function is suggested for the Q-h_1 relationship [10-14]:

$$\frac{Q}{bh_1}=f\left(\frac{\sqrt[3]{\frac{Re^2}{We}}}{20000}\right)=f\left(\frac{\sqrt[3]{\frac{\sigma h_1}{\rho \upsilon^2}}}{20000}\right) \tag{5}$$

The aim of this paper is to determine the Q-h_1 relationship in case of weir of $h_1<0.06$ m.

2. DESCRIPTION OF THE INSTALLATION

In the hydraulic laboratory of the Faculty of Civil Engineering in Subotica, a weir was installed in the flow direction at the downstream end of the experimental channel, having width of 0.1 m and length of 2.2 m (Figure 9).

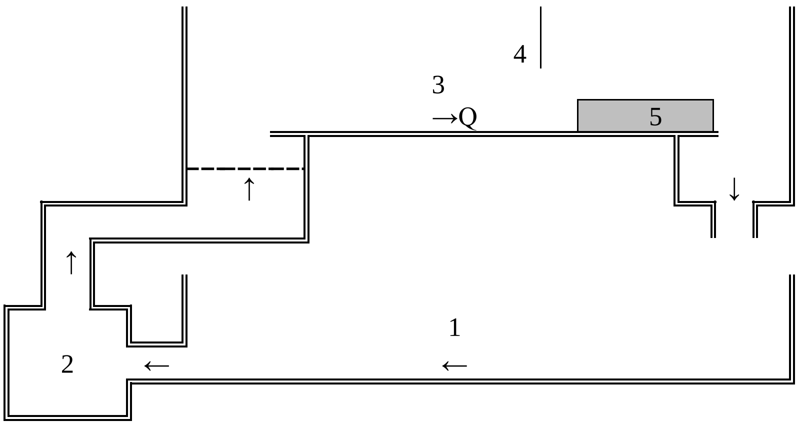

Figure 9 Experimental installation
1 - water tank, 2 - pump, 3 - channel of width b, 4 - gauge, 5 - weir of height P and length L

Water was brought into the channel from a tank by pump, producing modular flow over the weir, by then either returned to the tank through pipes, or taken to the water collecting vessel.

The crest with of the investigated weir was b=0.1 m, the length was L=0.095-0.5 m and the height was P=0.0678-0.0711 m (Table 2). The upstream and downstream faces of the weir were vertical, and the upstream and downstream horizontal edges were both sharp.

L (m)	0.095	0.19	0.5
P (m)	0.0678	0.0683	0.0711
$h_{1min} \div h_{1max}$ (m)	0.0034-0.0653	0.0038-0.0646	0.0046-0.0619
h_1/L	0.04-0.69	0.02-0.34	0.01-0.12
Number of measurements	62	68	42

Table 2 Basic characteristics of the tested series

In accordance with the recommendation of the international standard, the measuring section was located $3h_{1max}$=3*0.0619 m=0.1857 m<0.24 m<$4h_{1max}$=4*0.0653 m=0.2612 m upstream to the upstream face of the weir (Table 2).
The water level was measured using a gauge of ± 0.1 mm accuracy.
Capturing of water lasted at least 25 seconds. The mass of the water was measured using a scale accurate to 5 grams (within the range of up to 15 kg) and accurate to 10 grams (in the range between 15 kg and 150 kg).
The temperature of the water was measured near the measuring section. It varied between 19 and 21°C, averaging at 19.8°C. Water density was established using a measuring cylinder with a volume of 1 dm^3, intended for water having temperature of 20°C. The density of the water was 1 kg/dm^3. Therefore, the discharge was calculated using the following equation:

$$Q=\frac{G_{vessel+water}-G_{vessel}}{t}\ (l/s) \tag{6}$$

where $G_{vessel+water}$ is the combined mass of the vessel and the water contained (kg), G_{vessel} is the mass of the vessel only (kg), and t is the duration of water derivation (s).
Two types of errors have been identified in the paper: in determining the discharge and in determining the discharge coefficient. The discharge determination error is calculated using the equation: Error (%)=100*(Q_j-$Q_{(6)}$)/$Q_{(6)}$, where the Q_j discharge of water is calculated using the functions specified in Figures 11 and 12, and $Q_{(6)}$ is calculated using equation (6). The error in determining the discharge coefficient is calculated using the equation: Error (%)=100*(m_j-$m_{(1)}$)/$m_{(1)}$, where m_j is the discharge coefficient calculated using equation (2) and (3) and Figure 2, and $m_{(1)}$ is calculated using equation (1).

3. MEASUREMENT RESULTS

On December 28th of 2018, January 10th, February 11th-12th and 19th-20th of 2019, 42-68 measurements were performed by flow heads 0.0038-0.0653 m (Table 2).
Using equation (1) for each measurement, the discharge coefficient m has been determined (Figure 10).

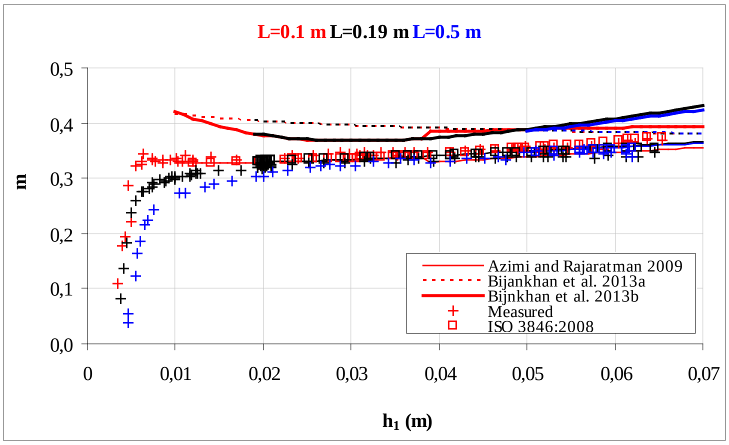

Figure 10 Measured values and values of discharge coefficient determined according to the international standard, compared with the results of the tests performed by Azimi and Rajaratnam (2009) and by Bijankhan et al. (2013)

Using Figure 2, equation (2) produced values of discharge coefficient which were in accordance with the international standard. Using equations (3) and (4), the Azim and Rajaratnam (2009) and Bijankhan et al. (2013) functions were presented.
The Q-h_1 relationship for $h_1/L<0.1$ was determined according to function (5) (Figure 11) and according to function $Ks/P=f(h_1/P)$ for $h_1/L>0.1$ (Figure 12).

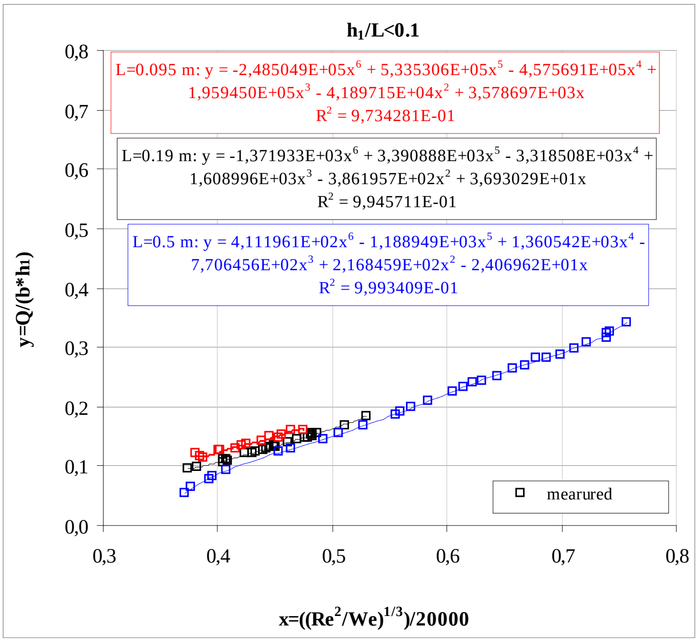

Figure 11 Functions (5) for the examined weirs

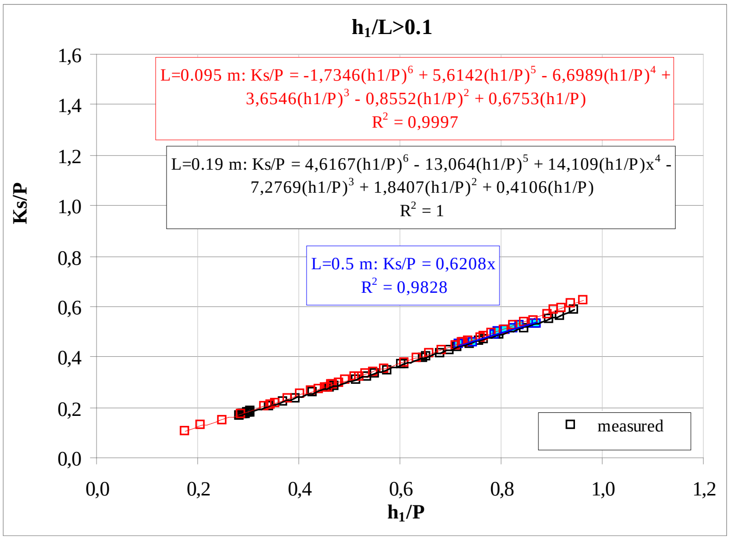

Figure 12 Functions $Ks/P=f(h_1/P)$ for the examined weirs

Function $Ks/P=f(h_1/P)$ exploits variables Ks/P and h_1/P used in equation (4).

4. DISCUSSION

1. The investigated case does not meet the requirements of the international standard at all (for *b* and *P*), or it meets it partially (h_1 and h_1/L). According to the values of h_1/L, the measurement includes states when the weir is treated as a long-crested weir, a broad and short-crested weir (Table 2).
2. Hager and Schwalt (1994) examined weir of length L=0.5 m (Table 1). For flow head h_1=0.05 m, relative flow head is h_1/L=0.1, which makes the limit between the long-crested and the broad-crested weir (Figure 13).

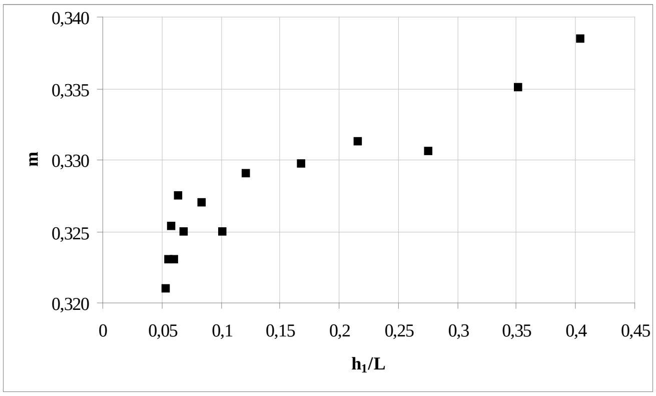

Figure 13 Change of the discharge coefficient in function of the relative flow head in the test series of Hager and Schwalt (1994)

These authors have highlighted that - in accordance with the international standard - the Q-h_1 relationship changes at $h_1/L=0.1$.
Zachoval et al. (2014) come to similar result by examining a weir length of L=0.5 (Table 1). Based on L=0.5 and the value of $h_1/L=0.12$, the flow head becomes $h_1=0.06$ m. Therefore, the values of $h_1/L=0.12$ and $h_1=0.06$ are mutually related. According to this, the limit between the long-crested and the broad-crested weir is $h_1/L=0.12$.

3. In accordance with the international standard for $h_1/L>0.1$, Azimi and Rajaratnam (2009) and Bijankhan et al. (2013) have established a Q-h_1 relationship using the geometric characteristics of the weir. This relationship applies to $h_1<0.06$ m as well. In case of a broad-crested weir, the following found to be true: for $h_1/L>0.1$ ($h_1>0.0095$ m for L=0.095 m, $h_1>0.019$ m for L=0.19 m and $h_1>0.05$ m for L=0.5 m) the viscosity and water surface tension do not influence the Q-h_1 relationship.
According to Figure 10, in this flow domain, out of the mentioned functions, the functions of the international standard and the functions established by Azimi and Rajaratnam (2009) were the closest to the measured values. The error margins of the discharge coefficient are (Figure14 and Table 3): a) ranging between -3.15% and +5.44% with the function from the international standard and b) ranging between -5.60% and +6.15% with the function established by Azimi and Rajaratnam (2009).

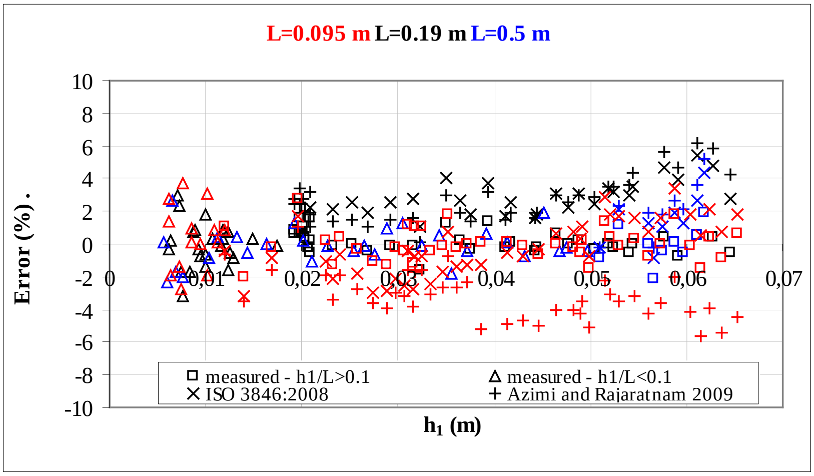

Figure 14 Errors in the discharge coefficient and discharge in function of the flow head

L (m)	0.095		0.5
ISO 3846:2008	-3.15% ÷+3.45%	+1.05% ÷+5.44%	-0.90% ÷+4.36%
Azimi and Rajaratnam (2009)	-5.60% ÷+1.06%	+0.07% ÷+6.15%	-0.21% ÷+5.20%
$h_1/L\leq0.1$	-2.79% ÷+3.69%	-3.24% ÷+3.02%	-2.32% ÷+2.61%
$0.1<h_1/L$	-2.04% ÷+2.82%	-1.57% ÷+1.6%	-2.14 %÷+1.93%

Table 3 Error margins of flow and discharge coefficients

In order to reduce these margins, functions shown in Figure 12 for the calculation of discharge have been established. In these cases, the error range in determining discharge is between -2.14% and +2.82%.

4. Data for $h_1/L<0.1$ ($h_1<0.0095$ m for L=0.095 m, $h_1<0.019$ m for L=0.19 m and $h_1=0.05$ m for L=0.5 m) does not belong to the broad-crested weir, but to the long-crested weir, with which the international standard does not deal.
The tests performed by Azimi and Rajaratnam (2009) and by Bijankhan et al. (2013) have already showed that the functions for the Q-h_1 relationship corresponding to long-crested weirs are different from the functions for the Q-h_1 relationship corresponding to the broad-crested weirs. This conclusion is supported by the following: the difference in the Q-h_1 relationship is due to the higher friction in case of the weir treated as long-crested. For a broad-crested weir the relative channel length is $2.5<L/h_1<10$, while for the long-crested weir this value is $10<L/h_1<\infty$. This observation is confirmed by Figures 10 and 11: for identical discharge, the required flow head in case of the long-crested weir is increasing by the length of the weir.
Therefore, in accordance with the international standard, Hager and Schwalt (1994) and Zachoval et al. (2014) found, that in addition to the geometric properties of the weir, viscosity and water surface tension also influence the Q-h_1 relationship of flows in long-crested weirs. For $h_1/L<0.1$, it is justified to use a function which besides geometry characteristics account for both the viscosity and surface tension effects, such as functions of the type (5).
With the decrease of the flow head, the measurement becomes increasingly sensitive to the measurement accuracy of the flow head. For these errors, cases with $h_1\leq0.0055$ m were excluded from consideration.
Using function of the type (5) shown in Figure 11 for $h_1/L<0.1$, the error in the determination of flow is brought to be -3.24% to +3.69% (Figure 14 and Table 3).

5. CONCLUSION

To expand the international standard ISO 3846:2008, relationship between discharge *Q* and the flow head $h_1<0.06$ m has been investigated in modular flow over a full-width weir having sharp edges, without upstream and downstream ramps.
The basic characteristics of the new method for determining the Q-h_1 relationship are:

- viscosity and water surface tension have impact on the Q-h_1 relationship at the long-crested weir only, and
- using Q-h_1 relationship shown in Figures 11 and 12, the error margins are between -3.24% and +3.69% for long-crested weirs, and between -2.14% and +2.82% for broad and short-crested weirs.

Following research should be aimed at the Q-h_1 relationship for $h_1<0.06$ m in case of weirs with upstream and downstream ramps.

LITERATURE

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NEPOTOPLJENO PRELIVANJE MALIH PROTICAJA NA PRAGU SA VERTIKALNIM KRAJEVIMA

Rezime: *Međunarodni standard ISO 3846:2008 je namenjen za utvrđivanje proticaja vode Q pri visini prelivnog mlaza koji je veći od h_1=0.06 m, kod pravougaonog, nesuženog praga sa oštrim ivicama i vertikalnim zidovima na oba kraja praga. Tema ovog rada je nepotopljeno prelivanje pri h_1<0.06 m. U ovoj oblasti prelivanja se javlja uticaj viskoznosti i površinskog napona vode. Stav srtučne literature u vezi utvrđivanja proticaja u ovoj oblasti strujanja nije jednoznačan: ili a) isključuje se iz razmatranja ova oblast strujanja zbog uticaja viskoznosti i površinskog napona vode, ili b) zanemaruje se ovaj uticaj pri utvrđivanju veze Q-h_1. Od 28. decembra 2018. godine do 20. februaru 2019. godine u hidrauličkoj laboratoriji Građevinskog fakulteta u Subotici (Srbija) ispitivani su pragovi dužine 0.095, 0.19 i 0.5 m. Rad dopunjuje međunarodni standard za utvrđivanje veze Q-h_1 pri h_1<0.06 m.*

Ključne reči: *prag bez rampi, prag sa oštim ivicama, nepotopljeno prelivanje, viskoznost vode, površinski napon vode*