NEW APPROACH FOR DETERMINING DISCHARGE ON A FULL WIDTH, TILTED THIN-PLATE WEIR

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Summary: *The international thin-plate weir standard refers to vertical weirs. The aim of this paper is to determine the possibility of measuring the discharge of a modular flow of water over a full-width, tilted thin-plate weir, referred to as inclined or pivot weir as well. The results of the previous analyses: deal only with ventilated discharge. Within the scope of the research of the possibility of measuring runoff hydrograph using thin-plate weir under modular flow, of the tested solutions, the one recommended for practical use is the full-width, tilted weir. Based on the measurements conducted at the Faculty of Civil Engineering in Subotica (Serbia), in this paper, the limits between ventilated and unventilated flows are specified, and proposals are made for the measurement of the entire range of discharge (ventilated and unventilated) of modular flow over a full-width, tilted thin-plate weir.*

Keywords: *tilted thin-plate weir, full-width weir, modular flow, ventilated flow, unventilated flow*

1. INTRODUCTION

1.1. International standard

The international standard concerning thin-plate weirs refers to the vertical, contracted and full-width weirs [1, 2]. The equations in Table 1 are used for the calculation of the discharge of water in ventilated modular flows, for heads H≥0.03 m, with viscosity and surface tension effects ignored.

Kindsvater-Carter	Rehbock
$Q=C_d\frac{2}{3}\sqrt{2g_n}b_e h_e^{3/2}$	$Q=C_e\frac{2}{3}\sqrt{2g_n}Bh_e^{3/2}$
b/B=1: $C_d=0.602+0.075H/P$ b/B=0.8: $C_d=0.596+0.045H/P$ b/B=0.6: $C_d=0.593+0.018H/P$ b/B=0.5: $C_d=0.592+0.01H/P$ b/B=0.4: $C_d=0.591+0.0058H/P$	b/B=1: $C_e=0.602+0.083H/P$

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b/B=0.2: C_d=0.589-0.0018H/P	
b/B=1: b_e=B-0.0009 (m) b/B=0.8: b_e=b+0.0042 (m) b/B=0.6: b_e=b+0.0036 (m) b/B=0.4: b_e=b+0.0027 (m) b/B=0.2 b_e=b+0.0024 (m)	
h_e=H+0.001 (m)	h_e=H+0.0012 (m)
H/P<2.5	H/P≤4
H≥0.03 m	0.03 m≤H≤1 m
b≥0.15 m	B≥0.3 m
P≥0.10 m	0.06 m≤P≤1 m
(B-b)/2≥0.1 m	

Table 1 Equations for discharge calculation according to the international standard for modular flow

In Table 1 g_n=9,81 m/s^2 is acceleration due to gravity, B is channel width (m), b≤B is weir width (m), H is upstream head (m) and P is the height of the weir (m). For H/P≤4 the head-measurement section is located (2↔8)*H_{max} upstream of the weir, where H_{max} is the maximum upstream head.
In this paper tilted thin-plate weir is being examined, referred to as inclined or pivot weir as well [3-5]. The inclination angle θ is measured in degrees from the bottom of the channel on the downstream side of the weir, while α=90-θ is measured from the vertical.

1.2 Measurements and analysis for the calculation of discharge in modular flow over a tilted weir

Below is the review of data from the highlight literature on measurement and analysis for determining discharge in the modular, ventilated flow over the inclined weir. The effects of viscosity and surface tension on flow [3-8], which apply for upstream head heights greater than 0.04 m were ignored [3].

1.2.1 Overview of the results of measurements concerning the tilted weir

During the study of thin-plated weirs in France (1886-1887), Henry Bazin has investigated tilted weirs as well [6, 9-10]. Thin-plated weir of width b=1 m, height P=0.3481 m (θ=14.04°), 0.3511 m (θ=26.57°), 0.352 m (θ=45°) and 1.133 m (θ=14.04°, 26.57°, 45°, 56.31° and 71.57°) has been installed into a channel of width B=1 m [6]. The flow was ventilated [9]. The measurement section was located 5 m upstream of the weir [6]. As the upstream head varied between 0.2 and 0.447 m, and the maximum value for H/P=0.404 m/0.3481 m=1.16<4, the chosen location of the measurement section

($8*H_{max}=8*0.447=3.576$ m<5 m) was not in accordance with the international standard for vertical weirs.
The USBR measurements (1948) carried out in the Colorado Agricultural Experiment Station Hydraulic Laboratory (1932) and the Bureau of Reclamation Hydraulic Laboratory (1937) included tilted weirs of inclination angle θ=45° (P=0.0241-1.2875 m), 56.31° (P=0.0256-1.439 m) and 71.57° (P=0.021-1.5484 m) [6, 10]. A contracted weir was examined (b/B=0.6148 m/0.6306 m=0.975) [6]. The 1.6 mm thick weir crest had slope with 56° inclination on the downstream side [10]. The flow was ventilated. The head measurement section was located 3 m upstream of the weir [6]. As the upstream head varied between 0.1128 and 0.3776 m, the location of the measurement section ($8*H_{max}=8*0.3776=3.0208$ m>3 m) was in accordance with the international standard for vertical weirs. However, the above statement is not valid in sense of H/P, since it was higher than 4, it has even reached value H/P=0.3024 m/0.021 m=14.4.
In 1992 and 1993, at the U. S. Water Conservation Lab and Phoenix in the United States tilted weirs have been examined [6]. Two series were examined: USWCL (1992) and ARMTEC (1993). The USWCL series, regardless to its contraction b/B=1.2 m/1.229 m=0.976, has been treated by the literature as measurements made on a full-width weir [6, 8]. The inclination angles for this series (P=0.61 m) were θ=24°, 25.9°, 27.8°, 29.8°, 30.2° and 35°. In case of the contracted weir (ARMTEC, P=0.46 m), these properties were as follow: contraction b/B=1.14 m/1.229 m=0.928 with the corresponding inclination angles θ=16.2°, 22.4°, 28.6°, 36.4°, 43.6°, 54.2° and 63.4°, b/B=0.84 with angles θ=36.4°, 54.2° and 63.4°, b/B=0.57, b/B=0.57 with θ=36.4° and b/B=0.51 with angle θ=54.2°.[6] Modular flow (USWCL and partly ARMTEC) was also examined. The measurement section was located 1.2-1.4 m upstream of the weir. The upstream head varied between 0.0513 and 0.2003 m (USWCL) and between 0.0354 m and 0.1695 m (ARMTEC). As the highest value of H/P=0.2003 m/0.61 m=0.33<4 (USWCL) and H/P=0.1686 m/0.46 m=0.37<4 (ARMTEC), the location of the measurement section ($8*H_{max}=8*0.2003=1.6024$ m>1.2 m) was in accordance with the international standard for vertical weirs.
Shesha Prakash et al. (2011) examined a contracted weir (b/B=0.15 m/0.3 m=0.5) located at the downstream end of the channel [11]. The inclination angles were α=0°, 15°, 30°, 45° and 60°.
In the hydraulic laboratory at Tabriz University, Iran modular flow over a full-width weir of height P=0.2 m and inclination angle α=0°, 15°, 30° and 45° has been investigated [12]. The weir was located 5 meters downstream to the entrance of the channel having width B=0.25 m and length of 12 m. On each weir, 11 discharges were measured, with upstream heads varying from 0.02 to 0.22 m. For the maximum value of H/P=0.22 m/0.2 m=1.1<4. The location of the head measurement section was at 2 m upstream from the weir. Since $8*H_{max}=8*0.22=1.76$ m<2 m, the location of the head measurement section does not meet the recommendations of the international standard for vertical weirs. The measurement results are most likely valid only for ventilated flows.
Tests at the Water Research Institute of Tehran, Iran, were performed in a channel having width of B=1 m with a contracted (b=0.4 m P=0.65 m, b=0.6 m P=0.55 m and b=0.8 m P=0.4 m), inclined weir with an inclination angle of 20°<θ<90° [3].
In the Hydraulic Laboratory of the Department of Water Engineering, Imam Khomeini International University, Qazvin, Iran, full width thin plated weirs of width b=B=0.5 m, height P=0.232, 0.263 and 0.309 m, tilted by angle θ=30°, 40°, 54° and 90° have been investigated in a channel of length 12 m [5]. The weirs were installed 3 m downstream to

the inlet of the channel. The detailes of the weir crest and the method of aeration is not declared. Modular flow with overflow head in the range of 0.0255 to 0.145 m has been studied. For the maximum value of H/P=0.51<4. The measuring section was 0.6 m upstream to the weir. Since $8*H_{max}=8*0.145=1.16$ m>0.6 m, the location of the head measurement section met the recommendations of the international standard for vertical weirs.
There, the measurements on the modular flow over full-width, tilted, thin-plate weirs were performed in 1886-1887, 2004 and 2018. In all of the measurements but the last one, the distance between the measurement section and the weir was greater than the distance recommended in the international standard for vertical weirs.

1.2.2 Results of analyses for determining the discharge in case of modular flow over a tilted weir

In tilted weirs, the discharge of water is determined by the discharge function Q_{90} [6]:

$$Q_{\theta}=C_{a}Q_{90} \quad (1)$$

where Q_{90} is the function for the discharge calculation by Kindsvater and Carter (1959) given in Table 1 [9].
In 1985, Manz proposed the following function for determining the coefficient C_a [3]:

$$C_{a}=-5.89*10^{-12}\theta^{6}+1.202*10^{-9}\theta^{5}-8.35*10^{-8}\theta^{4}+3.422*10^{-6}\theta^{3}-2.217*10^{-4}\theta^{2}+9.035*10^{-3}\theta+ \quad (2)$$

The available literature does not indicate on the basis of which measurements this function was obtained.
In 2011, Shesha Prakash et al. proposed the following function for tilted weirs instead of equation 1 (b/B=0.5) [11]:

$$Q=KH^{n} \quad (3)$$

where K=f(α) and n=f(α) are coefficients.
Based on the results of full-width weir measurements performed in Tabriz (2014), equation 3 has been calibrated for different values of the angle of inclination. The authors did not define the dimensions for Q and H, nor did they declare the area of the use of the equations. The same authors used the following function $Q=C_d h_w^{1.5}$, where b=B and h_w=H [12]. The results of comparison of coefficient C_d for inclination angles $\alpha=15^o$, 30^o and 45^o, with the values of coefficient C_d for vertical weirs ($\alpha=0^o$), are shown on the charts. They were not processed further.
Based on the Ferro examinations (2012, 2013) 2017 and 2018, a new form of function 1 was proposed [4, 7]:

$$k_{s}/p=a\left(h/p\right)^{c} \quad (4)$$

where $k_s=Q^{2/3}/(b^{2/3}g^{1/3})$, p=P, h=H and $g=g_n$. Using the results of measurements on contracted and full-width weirs (1932, 1937, 1992 and 1993), for angles 0°≤θ≤80°, the following functions were determined a=f(θ) i c=f(θ) [7].
Bijankhan and Ferro in 2018 have again analized the above mentioned function 4 [5]. Based on the measurements carried out in Qazvin (2018) for inclination angles 30°≤θ≤90°, for the calculation of the discharged have proposed the following relationship:

$$Q=\left(\left[\left(206.9+0.801\theta^{-21.348}\right)/\left(272.25+\theta^{-21.348}\right)\right]^{\frac{3}{2}}/2^{\frac{1}{2}}\right)B\sqrt{2g}y_1^{\frac{3}{2}} \qquad (5)$$

where b=B, y_1=H and angle θ is in radians.
Therefore, in determining these functions, the results of full-width, tilted weir measurements were the only ones used just in case of function 5. Functions 1 and 2 are also usable for analyzing the results of the new measurements, since they have as well exploited the results of measurements performed on full-width, tilted weirs.

1.3 Measurement of the runoff hydrograph

In the scope of the runoff hydrograph measurements in case of modular flow over thin-plate weirs, the possibility of determining the point of adherence and the point of separation of the nappe was investigated [13-18]. For the this problem, in 2015 a series of tests was started in the hydraulic laboratory of the Faculty of Civil Engineering in Subotica for determining a suitable method for nappe aeration. Three solutions have been examined:
a) vertical, full-width, thin-plate weirs of various heights P equipped with an aerator device called „artificial finger",
b) vertical, contracted weir of height P=0.2 m, and
c) full-width, tilted weirs of various heights P.
Based on the comparison of measurement errors and taking into account the required modifications for making a thin-plate weir suitable for runoff hydrograph, the full-width, tilted weir is recommended for practical use, out of all tested solutions.
The following problems were discovered regarding the measurement of runoff hydrograph using a tilted, thin-plate weir:
• limit between the ventilated and unventilated flow needs to be specified, and
• solution for discharge measurement in unventilated flows, which is not considered the international standard, needs to be solved.
The following function was used for the unventilated state:
$Q/[B(P+H)]=f([Re^2/We]^{1/3}/20000)=f([(\sigma H)/(\rho\upsilon^2)]^{1/3}/20000)$
where $We=(2\rho gHb)/\sigma$ and $Re=((2gH)^{0,5}(bH)^{0,5})/\upsilon$ Weber and Reynolds number respectively, ρ is density, σ is the surface tension coefficient and ν is the kinematic viscosity coefficient of water.
In the paper presented in Niš (2018) the measurement results produced in Subotica (from 20. Octobre 2017 to 24. July 2018) [18]. For the calculation of the discharge specific functions of order 6 in respect to H have been proposed both for the aerated and not aerated nappes. In case of the not aerated nappe theese functions do not provide reliable result in the vicinity of H=0.

The aim of this work is to exploit the results for the aerated nappe already available in the scientific papers, and to resolve the problem highlighted above regarding the not aerated nappe.

2. DESCRIPTION OF THE INSTALLATION

At the hydraulic laboratory of the Faculty of Civil Engineering in Subotica, a thin-plate weir was installed on the downstream end of a canal (Figure 1).

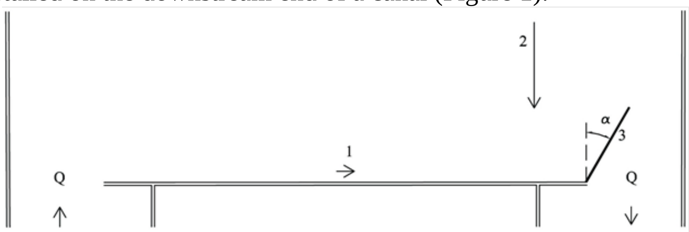

Figure 1 Experimental installation
1 - canal of width B=0.1 m and length of 2.2 m, 2 - gauge, 3 - thin plate weir, inclined to the angle α

Weirs of heights P=0.1, 0.15 and 0.2 m, width b=B=0.1 m and inclination angles α=10, 20 and 30^o were tested.
The rest of the test method followed the method described in the papers published in 2016, 2017, and 2018 [13-18].
The plexiglass weir had thickness of 5 mm, with crest thickness of 2 mm and slope from the downstream side was at an angle of 45°.
The water level was measured 0.18 m upstream of the weir using a gauge of ± 0.1 mm accuracy.
The water capturing lasted for at least 25 seconds. The weight of the water is measured using a scale accurate to 5 grams (within the range of up to 15 kg) and a scale accurate to 10 grams (ranging from 15 kg up to 150 kg).
During water capture, the temperature of the water was measured near the upstream section. The temperature varied between 19 and 21^{o}C, averaging at 19. 91^{o}C. Water density was established using a measuring cylinder with a volume of 1 dm^3, calibrated for water temperature of 20^{o}C. The density of the water was 1 kg/dm^3. Therefore, the discharge was calculated using the following equation: $Q(l/s)=(G_{vessel+water}-G_{vessel})/t$, where $G_{vessel+water}$ is the combined weight of the vessel and the water contained (kg), G_{vessel} is the weight of the vessel only (kg), and t is the duration of water derivation (s).
The error of determining the discharge coefficient is calculated using the equation: Error (%)=$100(m_j-m_{(6)})/m_{(6)}$, where m_j is the discharge coefficient, calculated in accordance with some of the functions listed in Figures 3 and 4, and $m_{(6)}$ is the discharge coefficient calculated using the following equation:

$$Q=m\sqrt{2g}\,bH^{3/2} \qquad (6)$$

where m is the discharge coefficient, which is the function m=f(H/P, b/B, H/b, α, We, Re).

3. MEASUREMENT RESULTS

Table 2 shows the number of measurements by series, measured between October 20, 2017 and July 24, 2018.

P (m)	0.2	0.2	0.2	0.15	0.1
α (°)	6	20	31.1	28.5	26.4
Number of measurements	21	25	74	61	60

Table 2 Number of measurements by examined series

The test was carried out so that the discharge of water was increased from zero to maximum in small increments, and then reduced to zero again through a similar procedure. At the point of separation, the upstream head increased rapidly. Measurement results are shown in Figure 2 and Table 3.

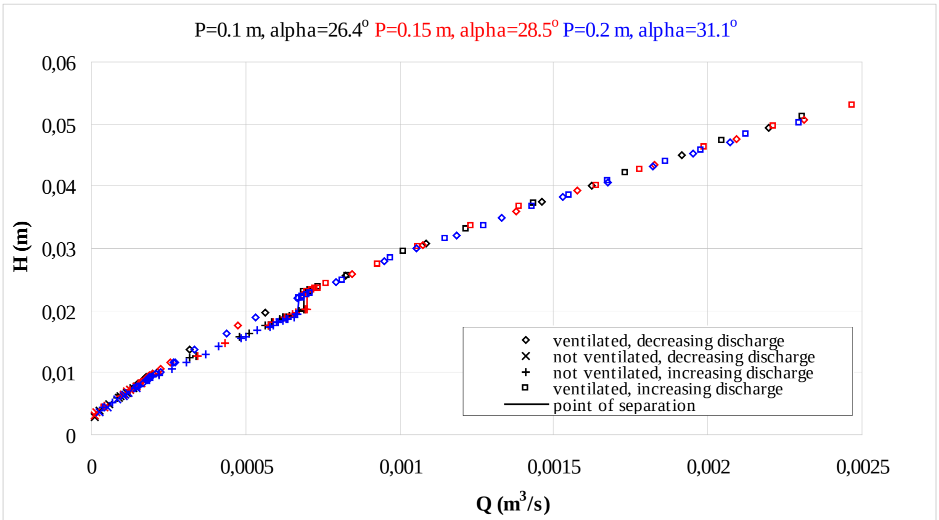

Figure 2 Relationship between the upstream head H and water discharge Q for weirs of height P=0.1-0.2 m and angle of inclination α=26.4-31.1°

P (m)	α (°)	Point of separation Q (m^3/s)	Point of separation H (m)	Point of adherence Q (m^3/s)	Point of adherence H (m)
0.1	26.4	0.00069	0.0201→0.0229	0.00013-0.00014	0.0073-0.0078
0.15	28.5	0.00070	0.0203→0.0230	0.00015-0.00016	0.0083-0.0084
0.2	31.1	0.00067	0.0193→0.0219	0.00014-0.00015	0.0074-0.0077

Table 3 Results of measurements regarding the discharge and upstream head for the point of separation and adherence of the nappe of the tilted weir

The results of measurements concerning function type 4 for the aerated nappe are presented in Figure 3.

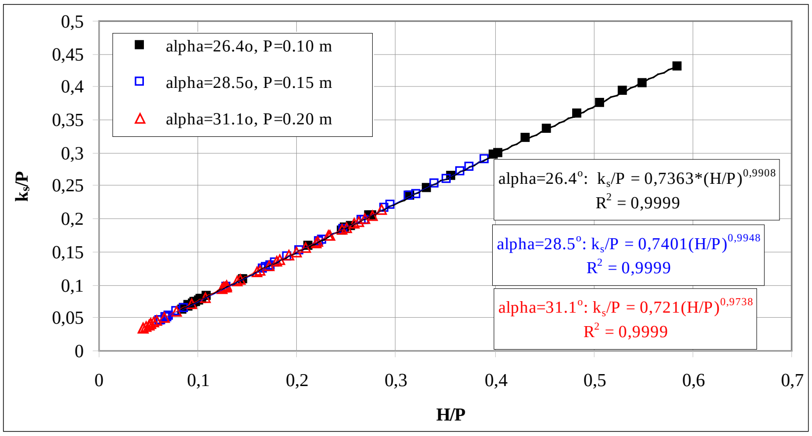

Figure 3 Function type 4 for the aerated nappe for weirs of height P=0.1-0.2 m and tilt angle α=26.4-31.1°

Equalling discharges by equations 4 and 6 results in discharge coefficient:

$$m = k_s^{\frac{3}{2}} \Big/ \left(2^{\frac{1}{2}} H^{\frac{3}{2}} \right) \tag{7}$$

For the calculation of m using the above equation, the k_s values shown in Figure 3 are to be used.

The results of the measurement of the discharge coefficient for the ventilated state are shown in Figure 4.

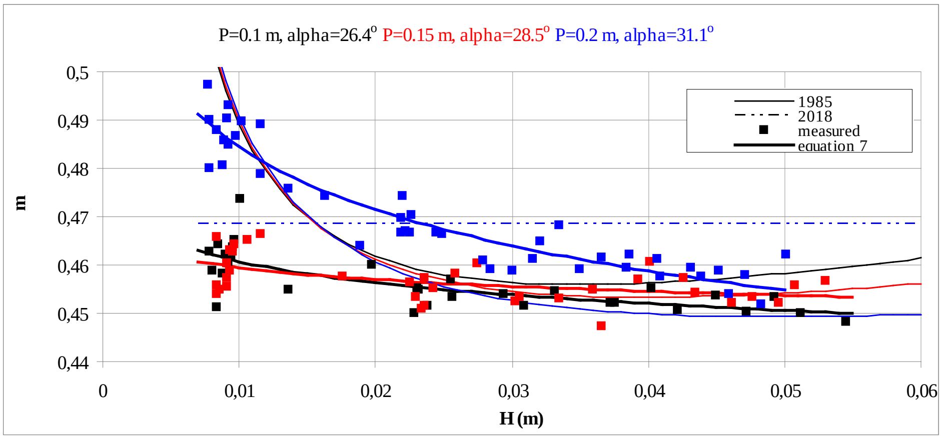

Figure 4 The discharge coefficient m in the function of the upstream head H for weirs of height P=0.1-0.2 m and angle of inclination α=26.4-31.1°

For unventilated flows, the results are shown in Figure 5.

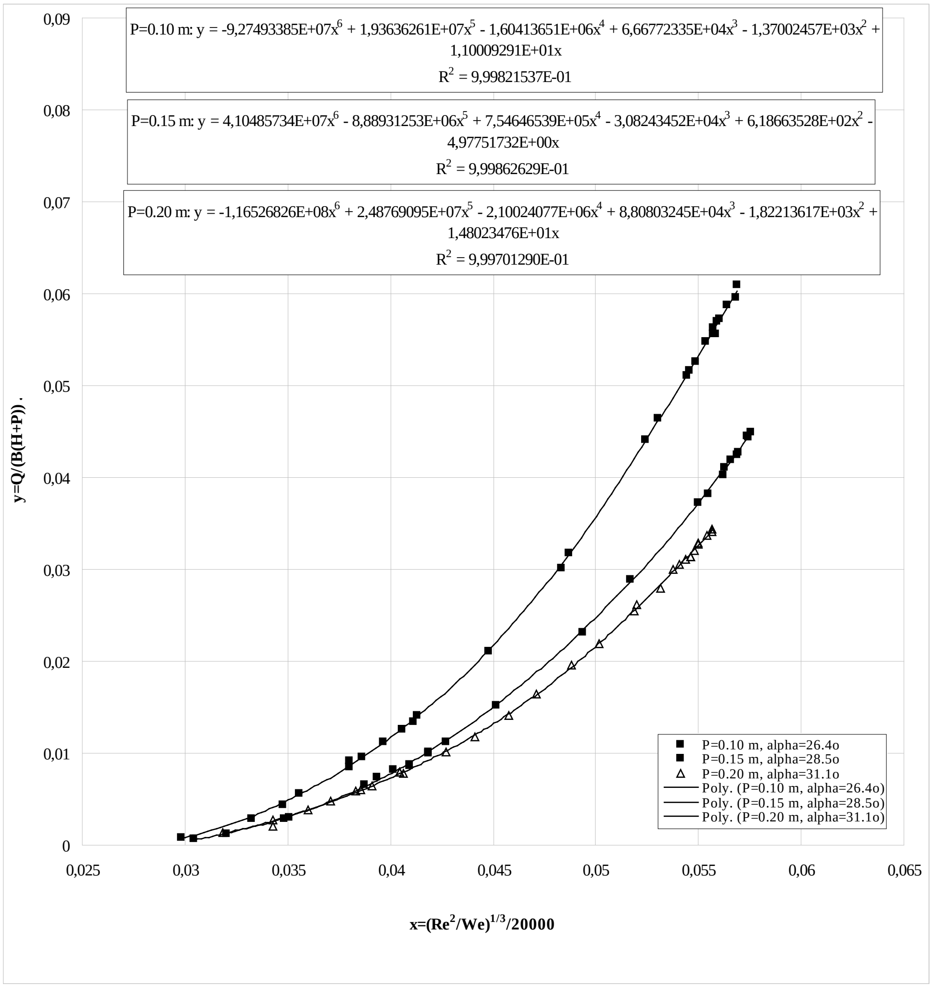

Figure 5 The function $Q/[B(P+H)]=f([(\sigma H)/(\rho v^2)]^{1/3}/20000)$ for the unventilated discharge over tilted weirs of height P=0.1-0.2 m and angle of inclination α=26.4-31.1º

4. DISCUSSION

1. As the maximum upstream head was H_{max}=0.0545 m (Figure 2), the distance between the measurement section and the weir crest was within the limits stated in the international standard for vertical weirs: 2*0.0545 m=0.109 m<0.18 m<8*0.0545 m=0.436 m.

2. According to the international standard for vertical weirs, the ventilated state occurs for H≥0.03 m, and according to the scientific literature, it occurs for H≥0.04 m. Tilted weir measurements in Tabriz (2014) and in Qazvin (2018) showed that this limit may be even lower than the values listed in the international standard. By making the tilted weir suitable for the measurement of the runoff hydrograph, it was concluded that the boundary between ventilated and unventilated water discharge depends on whether the discharge increases or decreases:
   - the ventilated state is achieved for decreasing discharge at H≥0.0077-0.0084 m, and for increasing discharge at H≥0.0203-0.023 m, and
   - the unventilated state is achieved for decreasing discharge at H≤0.0073-0.0083 m, and for increasing discharge at H≤0.0193-0.0229 m.

   By examining the tilted weir, it is found that:
   a) there are two boundaries between ventilated and unventilated flow over the weir, and
   b) the upstream head may be less than the values set in the international standard.
3. Functions 1, 2 and 5 are determined for ventilated discharge over a full width, tilted weir. Their charts shown in Figure 4 did not remain in the range of measurement results produced in Subotica (2017-2018).
   Due to this fact, new functions of type 7 are given in this paper for m=f(H, P, α). Using the new functions, in case of aerated flows the error in discharge coefficients is between -2.75% and +2.35% (for P=0.1 mm), -1.61% and +1.68% (for P=0.15 m) and -1.61 and +1.93% (for P=0.2 m) (Figure 6).

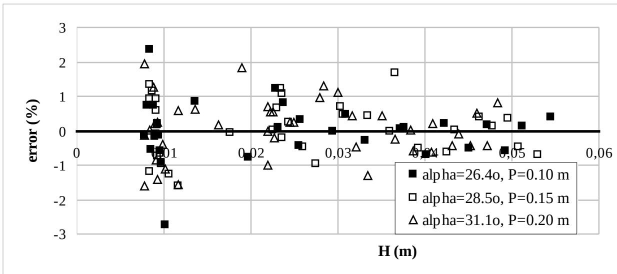

Figure 6 Error of the discharge coefficient m in the function of the upstream head H for thin-plated weirs of height P=0.1-0.2 m and angle of inclination α=26.4-31.1°(ventilated discharge)

These results apply only to the aforementioned tilted weirs. Because of this, further investigation of ventilated modular flow over a tilted weir is required.

4. The above conclusion is also valid for the unventilated state.
   If the equations given in Figure 4 are used, in the case of unventilated discharge, the error for determining the water discharge will be between -1.14 and +1.53% (for P=0.1 m, H>0.006 m), -0.48 and +1.30% (for P=0.15 m, H>0.0073 m) -1.78 and +1.93% (for P=0.2 m, H>0.0075 m), for tilted weirs with the inclination angles of α=26.4, 28.5 and 31.1° (Figure 7).

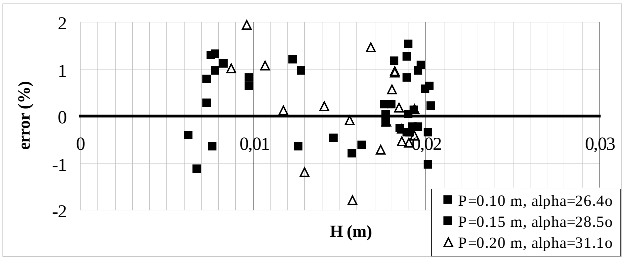

Figure 7 Error of the determination of the discharge Q in the function of the upstream head H for thin-plated weirs of height P=0.1-0.2 m and angle of inclination α=26.4-31.1° (ventilated discharge)

5. In case of the not aerated nappe for, overflow heads lower than 0.006-0.0075 m the measurement accuracy is not satisfactory.

5. CONCLUSION

This paper presents the results regarding discharge calculation in case of modular flow over a full width, tilted thin-plate weir, available in scientific papers (for aerated flow) as well as the results gained in Subotica (2017-2018) (for both aerated and not aerated flow). Unlike in the currently available scientific literature, the investigation in Subotica highlighted that two limits between the aerated and non aerated state exist: the point of adherence of the nappe and at the point of separation of the nappe.

Functions propost by the scientific literature for the aerated flow do not cover the range of measurements performed in Subotica (Figure 4). Based on theoretical considerations by Bijankhan and Ferro (2017), Di Stefano et al. (2018) and Bijankhan and Ferro (2018) in the current work new functions of type 7 are proposed for the discharge coefficient calculation [4-5, 7].

In the paper, as a supplement to the scientific literature, new functions for the same weirs for determining the discharge in case of unventilated flows is given (Figure 5). The new functions provide correct results in the domain of H=0.

The acquired experience indicates the need for further measurements (for example, for b>0.1 m) and their analysis in order to create a clearer picture of the physics of modular flow over full width, tilted, thin-plate weirs.

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NOVA METODA ZA UTVRĐIVANJE PROTICAJA NA NESUŽENOM, NAGNUTOM, OŠTROIVIČNOM PRELIVU

Rezime: *Međunarodni standard oštroivičnog preliva se odnosi na vertikalan preliv. Cilj ovog rada je utvrđivanje mogućnost merenja proticaja pri nepotopljenom prelivanju vode na nesuženom, nagnutom prelivu. Rezultat dosadašnjih analiza: bavi se samo aerisanim prelivanjem. U okviru istraživanja mogućnost merenja hidrograma oticaja oštroivičnim prelivom pri nepotopljenom prelivanju, od ispitivanih rešenja za upotrebu u praksi je preporučeno korišćenje nesuženog, nagnutog preliva. Na osnovu merenja na Građevinskom fakultetu u Subotici (Srbija) u ovom radu je vršeno preciziranje granice između aerisanog i neaerisanog prelivanja, i dati su predlozi za merenje proticaja u celom dijapazonu (neaerisanom i aerisanom) nepotopljenog prelivanja preko nesuženog, nagnutog, oštroivičnog preliva.*

Ključne reči: *nesuženi nagnuti oštroivični preliv, nepotopljeno aerisano i neaerisano prelivanje*