CONTRACTED THIN-PLATE WEIR FOR MEASURING DISCHARGE HYDROGRAPHS

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Summary: *The aim of the testing series that started in 2015 in the hydraulic laboratory of the Faculty of Civil Engineering in Subotica is preparation of the non-submerged thin-plate weir for measuring discharge hydrographs. Fixing the points of adherence and separation is the essence of the preparation. This presents novelty in respect to the current international standard. Earlier papers of this author presented the experimental results of full-width thin-plate weirs of different height P equipped with nappe aerator called artificial finger. This paper presents the results of a thin-plate weir of height P=0.2 m with side contraction.*

Keywords: *hydrograph, non-submerged weir, thin-plate weir, contracted weir*

1. INTRODUCTION

In the channel of rectangular cross-section of width B a thin-plate weir of width b<B and height P orthogonal to the flow direction is installed (Figure 1).

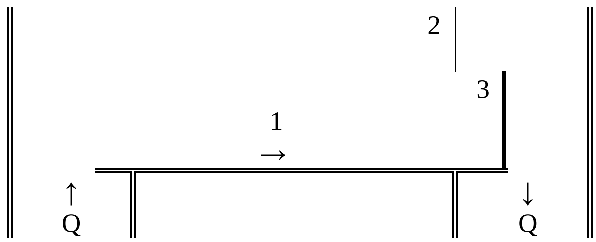

Figure 1 Experimental installation
1 – channel, 2 – gauge, 3 – contracted thin-plate weir

In case of non-submerged overflow:

- for decreasing discharge the adherence point separates the aerated and non-aerated nappe, and
- for increasing discharge the separating point is the limit between the non-aerated and aerated nappe [1-4].

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Insufficient aeration of the discharge nappe makes impossible stabilization of these two points. Therefore, for measuring weir hydrographs the discharge nappe needs to be sufficiently aerated.
The water discharge Q in non-submerged aerated overflow, in Republic Serbia is calculated by the following equation:

$$Q=m\sqrt{2g}\,bH^{3/2} \tag{1}$$

where m is the discharge coefficient, g the acceleration force of gravitation and H is the head of the nappe. Generally, the discharge coefficient is a function m=f(H/P, b/B, H/b, We=(2ρgHb)/σ, Re=($(2gH)^{0,5}(bH)^{0,5}$)/υ), where We and Re are Weber and Reynolds numbers, ρ the density, σ the surface tension coefficient and ν is the kinematic viscosity coefficient of water [1-10]. The impact of these numbers on the discharge coefficient occur at low values of b, or H, or both b and H.
The valid international standards [11-12] and recent studies [7, 9, 13-14] for determining the discharge with aerated nappe recommend different equations (Table 1).

Kindsvater-Carter [11-12]	Rehbock [11-12]	Bagheri and Heidarpour 2010a [13]
$Q=C_d\frac{2}{3}\sqrt{2g_n}b_eh_e^{3/2}$	$Q=C_e\frac{2}{3}\sqrt{2g_n}Bh_e^{3/2}$	$Q=C_d\frac{2}{3}\sqrt{2g}bH^{3/2}$
b/B=1: $C_d=0.602+0.075\frac{H}{P}$ b/B=0.8: $C_d=0.596+0.045\frac{H}{P}$ b/B=0.6: $C_d=0.593+0.018\frac{H}{P}$ b/B=0.5: $C_d=0.592+0.01\frac{H}{P}$ b/B=0.4: $C_d=0.591+0.0058\frac{H}{P}$ b/B=0.2: $C_d=0.589-0.0018\frac{H}{P}$	b/B=1: $C_e=0.602+0.083\frac{H}{P}$	0.25≤b/B≤1: $C_d=0.324\exp\left(0.94\frac{b}{B}\right)*$ $*\ln\left(1+\frac{0.73\frac{H}{P}+3.64}{\exp(1.18\frac{b}{B})}\right)$
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	0<H/P<9
H≥0.03 m	0.03 m≤H≤1 m	
b≥0.15 m	B≥0.3 m	(0.08 m≤b≤0.32 m)
P≥0.10 m	0.06 m≤P≤1 m	(0.08 m≤P≤0.18 m)
(B-b)/2≥0.1 m		

Bagheri and Heidarpour 2010b [14]	Aydin et al. 2011 [7]	Gharahjeh et al. 2015 [9]
$Q=C_d\frac{2}{3}\sqrt{2g}bH^{3/2}$	$Q=v_w bH$	$Q=v_c bH$
0.25≤b/B≤1: $C_d=0.79\ln\left(\begin{array}{l}2.206+0.242\frac{H}{P}*\\ *(\frac{B}{b})^{0.0615}\end{array}\right)$	0.3≤b/B≤1: $v_w=c_1+$ $+c_2H+c_3H^{1.5}$ $c_1=0.252-$ $-0.068\frac{b}{B}+0.002(\frac{b}{B})^2$ $c_2=3.937+$ $+0.760\frac{b}{B}+2.426(\frac{b}{B})^2$ $c_3=-2.238-$ $-2.856\frac{b}{B}-1.427(\frac{b}{B})^2$	$v_c=c_c\sqrt{2gH}$ b/B≥0.3: $c_c=0.153(\frac{b}{B})^2-$ $-0.0922(\frac{b}{B})+0.4136$
0<H/P<10		
	(0.0233 m≤H≤0.1578 m)	(0.01 m≤H≤0.54 m)
(0.08 m≤b≤0.32 m)	(0.1 m≤b≤0.32 m)	
(0.08 m≤P≤0.18 m)	(P=0.1 m)	(P≥0.1 m)

Table 1 Functions for the calculation of the discharge coefficient of aerated overflow according to international standard [10-11]

As illustrated in the given table the limit head of discharge nappe for influence of Weber and Reynolds numbers to overflow is not one number, but rather diapason of 0.01 m≤H≤0.03 m. Due to this fact, such weir cannot measure hydrographs flow. The way for solution of this problem was opened by the examination aimed to fix adherence and separation points: the impact of Weber and Reynolds numbers on overflow is negligible for the increasing discharge from the separation point, and for reducing flow to the point of adherence [1-4]. This statement is confirmed in the hydraulic laboratory of the Faculty of Civil Engineering in Subotica where was tested the thin-plate weir of width b=B=0.1 m and head P=0.1, 015 and 0.2 m. The weir was located at downstream edge of the channel with the subsequent cascade. The weir was supplied with nappe aerator called artificial finger or strip for aerating. Artificial finger is the metal sheet of 0.03 m width bent into L-shape. The length of horizontal arm of the artificial finger is 0.065 m. In order to provide sufficient supply of air for aeration of the nappe uniformly throughout the entire width of the weir and to ensure water overflow without backwater, the following is required: a) free distance of constant width δ=0.0015 m between the horizontal arm of the artificial finger and the downstream side of the thin-plate weir and b) level difference of Δz=0.016 m between the weir crest and the horizontal part of the artificial finger. Disregarding overflow height, the adherence point was stable: it occurred with H=0.01 m. Discharge of the separation point was decreased with the increase of the weir height (Table 2).

P	Q	H (m)	H (m)
(m)	(m^3/s)	Neaer. stanje	Aer. stanje
0.10	0.00053	0.0178	0.0194
0.15	0.00050	0.0172	0.0188
0.20	0.00049	0.0167	0.0182

Table 2 Discharges and heads of the nappe of the separation point for examined heights of the weir

The link between water discharge and aerated nappe head is described by the functions of the international standard: for increasing flow with H≥0.0182↔0.0194 m, and for reduced flow at H≥0.01 m:

- according to Kindsvater-Carter for the entire tested diapason (for P=0.1 and 0.15 m), i.e. for 0.01 m≤H≤0.0182 m (for P=0.2 m) and
- according to Rehbock for 0.0182 m<H<0.04 m (for P=0.2 m).

Errors of the discharge coefficient are between -2.3 and +4.8% (for P=0.10 m), -1 and +3.6% (for P=0.15 m) and for diapason 0.01 m≤H≤0.0182 m, calculated according to Kindsvater-Carter are between -1.5 and +1.6%; and for diapason 0.0182 m<H<0.04 m according to Rehbock are between -1 and +1.1% (for P=0.20 m). Due to the limits of applicability of the mentioned function, in the calculation of aerated nappe, it is important to know whether it is increasing or declining flow rate.

This statement is also important for non-aerated nappe [15]. In thin-plate weir equipped with artificial finger the influence of the Weber and Reynolds numbers to overflow is significant for increasing flow to the separation point (H≤0.0167↔0.0178 m), and for decreasing flow from the adherence point (H≤0.009 m) [1-4]. Regardless of whether the value of the flow increases or decreases for non-aerated overflow the valid is only one function Q=f(H). This function is determined in two variants:

- variant A: $\frac{Q}{B(P+H)}=f\left(\left(\frac{Re^2}{We}\right)^{\frac{1}{3}}\frac{1}{20000}\right)=f\left(\left(\frac{\sigma H}{\rho\nu^2}\right)^{\frac{1}{3}}\frac{1}{20000}\right)$ and
- variant B: $\frac{m}{m_{Kindsvater\text{-}Carter}}=f\left(1000\left(\frac{We}{Re^2}\right)^{\frac{1}{3}}\right)=f\left(1000\left(\frac{\rho\nu^2}{\sigma H}\right)^{\frac{1}{3}}\right)$, that should be used with equation (1).

With non-aerated nappe for H≥0.005 m (for P=0.10 m), H≥0.0048 m (for P=0.15 m) and H≥0.0053 m (for P=0.20 m) error for the determination of discharge (variant A), or discharge coefficient (variant B) is:

- between -1.6 and +1.6% (for P=0.10 m), -2.1 and +2.4% (for P=0.15 m) and -2 and +2% (for P=0.20 m) with variant A, or
- between -2.8 and +2% (for P=0.10 m), -3 and +1.8% (for P=0.15 m) and -1.2 and +2.8% (for P=0.20 m) with variant B.

For non-aerated nappe is, thus, obtained smaller error using the functions described by the variant A.

For nappe aeration in case of non-submerged weir with flow contraction Bos (1987) recommended that the downstream water level needs to be 0.05 m below the weir crest level [16]. Contracted weir of $0.0167 \leq b/B \leq 0.25$ ($0.005\ m \leq b \leq 0.075\ m$) having height of $0.04\ m \leq P \leq 0.16\ m$ was tested in a B=0.3 m wide channel of rectangular cross-section [5]. The weir was placed at the downstream end of the channel with subsequent cascade. In case of this weir additional nappe ventilation was not necessary since air could get below the water nape, as stated by Aydin et al. (2002). The examined heads of the discharge nappe were between $0.0103\ m \leq H \leq 0.3018\ m$ [10]. The location of the contracted weir ($0.01 m \leq b \leq 0.32\ m$) installed in a channel of width B=0.32 m at the downstream end of the channel was the same at Gharahjeh et al. (2015) [9]. In addition to the use of the artificial finger, therefore, another option for weir aeration emerged: for measuring discharge hydrographs should be used non-submerged contracted weir located at the downstream end of the channel followed by cascade is required.
The aim of this paper is testing the stability of the adherence and separation points of the contracted thin-plate weir placed at the downstream end of the channel followed by cascade. In addition to the use of the artificial finger for aeration of the nappe, this is an additional novel solution to make the contracted thin-plate weir suitable for measuring discharge hydrographs.

2. INSTALLATION DESCRIPTION

In the hydraulic laboratory of the Faculty of the Civil Engineering in Subotica thin-plate weir has been installed on the downstream end of a B=0.1 m wide and 2.2 m long channel (Figure 1).
There was tested the weir of height P=0.2 m. Width of the contracted section weir was: b=0.03, 0.04, 0.05, 0.06 and 0.07 m.
All other conditions of investigation were equal to those described in paper published in 2016 and 2017 (1-4).
The plexiglass weir was 5 mm thick with crest thickness of 2 mm, and the notch angle of the dowstream side was 45^o.
The water level was measured 0.18 m upstream to the weir using a gauge of ±0.1 mm accuracy.
Derivation of water lasted at least 25 seconds. The weight of the water was measured by a scale of 5 grams accuracy (within the range of up to 15 kg) and 10 grams accuracy (up to 150 kg).
During water derivation the temperature of water was measured near to the upstream section. It varied between 19 and 21^{o}C and in average it was 19.92^{o}C during the whole period of measurement. Water density was established by a measuring cylinder of 1 dm^3 volume, calibrated for water temperature of 20^{o}C. The density of water was 1 kg/dm^3, therefore the flow rate was calculated by 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 contained water (kg), G_{vessel} is the weight of the vessel only (kg), and t is the duration of water derivation (s).
The error in the discharge coefficient was calculated by the following equation: $Error(\%)=[100(m_j-m_{(1)}]/m_{(1)}$, where m_j is the discharge coefficient, calculated in

accordance with one of the listed functions in Table 1, and $m_{(1)}$ is the discharge coefficient calculated by equation (1).

3. RESULTS OF THE MASUREMENTS

Measurements have been done from September 12th to October 10th 2017. The number of measurements was between 84 and 143 per series (Table 3).

b (cm)	3	4	5	6	7
Number of measurements	143	106	90	91	84

Table 3 Number of measurements per examined series

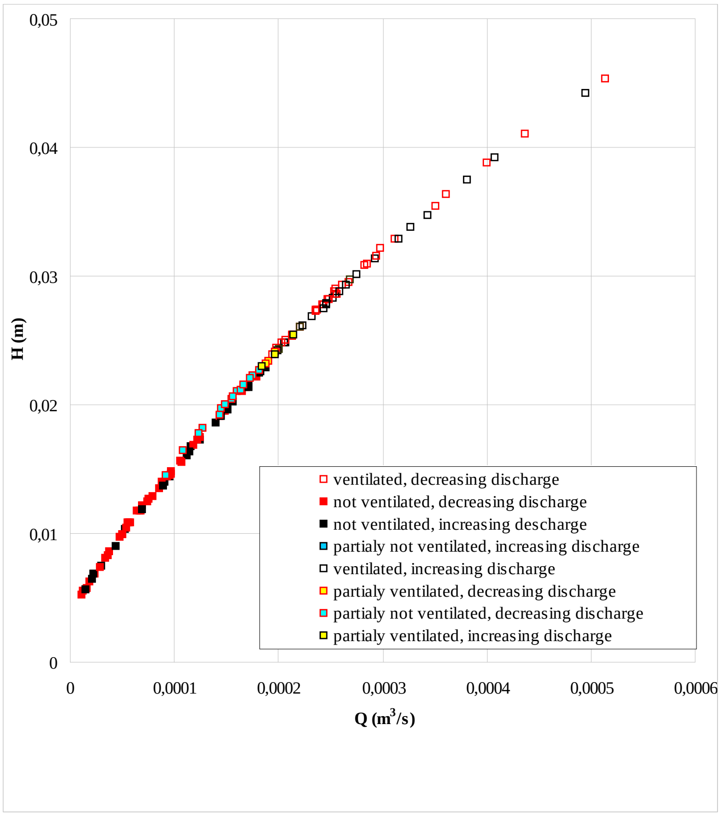

Figure 2 Dependency between discharge nappe head H and discharge Q for contracted weir b/B=0.3

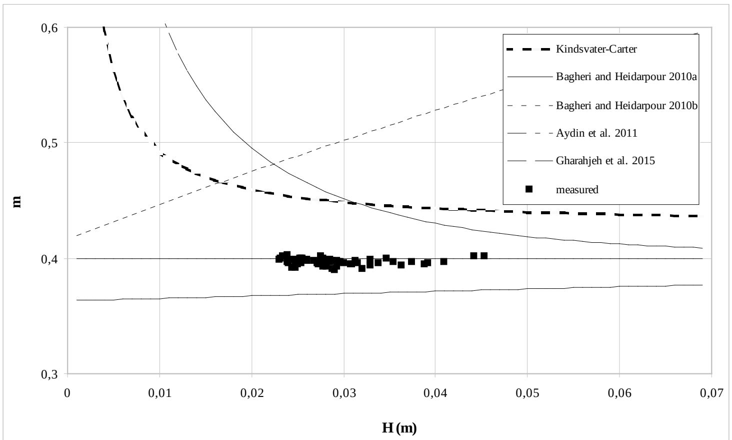

Figure 3 Discharge coefficient of aerated nappe m in the function of the head of discharge nappe H for contracted weir b/B=0.3

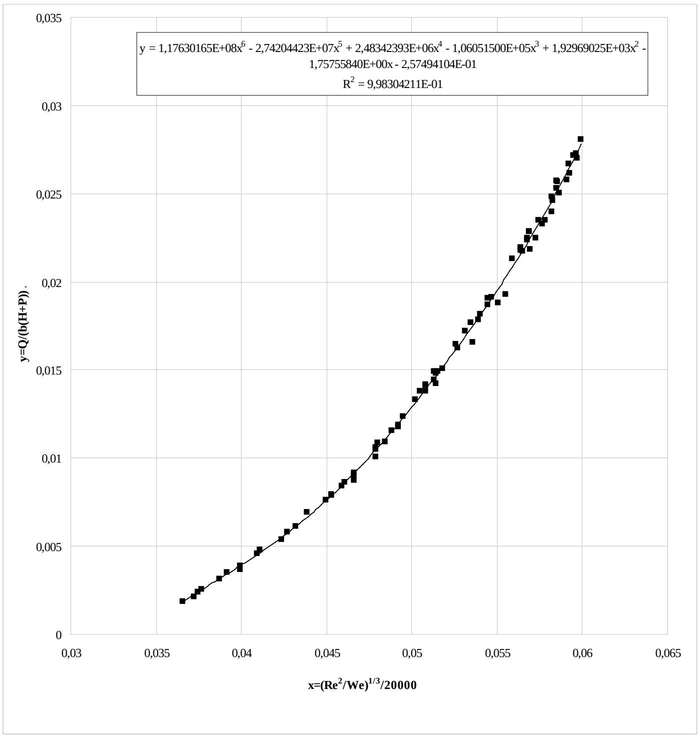

Figure 4 Function $\frac{Q}{b(P+H)}=f\left(\left(\frac{\sigma H}{\rho \nu^2}\right)^{\frac{1}{3}}\frac{1}{20000}\right)$ *for non-aerated discharge nappe of contracted weir b/B=0.3*

Testing was carried out applying minor increments in flow rate, starting from zero to the maximum flow, and then back to zero in a similar procedure. During the phase of rising flow rate the nappe was not aerated at the beginning, while later on the nappe got separated from the plate. This means that at a certain water discharge separation of the nappe occurred and the water head jumped to a higher level. In the opposite trend with a certain flow rate, the nappe adhered to the weir. This is the point of adherence of the nappe.

The stability of the separation point and adherence point was checked by tests repeated five times. All through the tested variants the separation point was stable for b/B=0.3 (Figure 2). Transition from non-aerated to aerated condition with contracted weir occurred at discharge 0.00019 m^3/s and head of H=0.023 m. Transition was continual without leap in head of discharge nappe. Transition from aerated to non-aerated condition occurred at the same flow and discharge head.

Result of the measurements of the discharge coefficient for aerated condition is illustrated in the Figure 3.

For the non-aerated nappe upon the variant A the results are illustrated in the Figure 4.

4. DISCUSION

1. Contrary to the former examinations in case of contracted weir b/B=0.3 the separation and adherence points merged. In the neighborhood of this point partially aerated water nappe occurred (Figure 2).
2. In case of the contracted weir the points of separation and adherence occur at higher discharge heads than in case of the full-width weir, while the tendency is increased by the intensity of contraction.
3. The measured discharge coefficients of the aerated contracted weir show best fit to the function proposed by Gharahjeh et al. 2015 (Figure 3).

Discharge coefficient errors of the aerated nappe were between -0.68% and +2.68% (Figure 5).

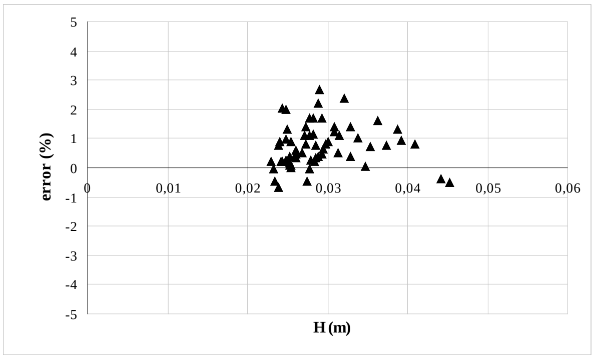

Figure 5 Discharge coefficient error m in function of discharge nappe head H for contracted thin-plated weir of b/B=0.3 (aerated nappe)

The upper statements regarding the contracted weir is novelty compared to the statements in the professional literature since here the limits of errors are also given.

4. With non-aerated contracted weir of b/B=0.3 for H≥0.0052 m errors in establishing the discharge are between -3.99 and +6.56% (Figure 6).

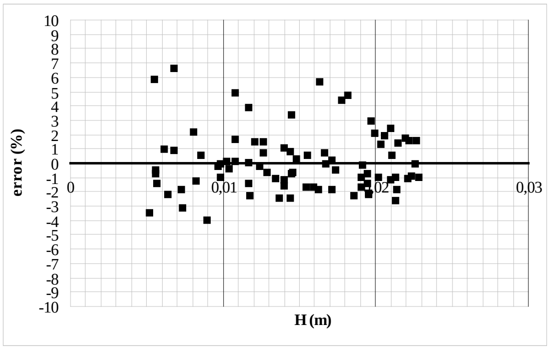

Figure 6 Error of establishing the discharge Q in function of discharge nappe head H for contracted thin-plated weir of b/B=0.3 (non-aerated nappe)

These results confirm our previously published findings: with non-aerated discharge water discharge is defined by a single equation with error limits provided.

5. CONCLUSION

In the hydraulic laboratory of the Faculty of the Civil Engineering in Subotica examination regarding the capacitance of non-submerged thin-plated weir for measuring discharge hydrographs has been continued. For the contracted weir of b/B=0.3, height of P=0.2 m it was find that the separation and the adherence points were stable.

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СУЖЕНИ ОШТРОИВИЧНИ ПРЕЛИВ ЗА МЕРЕЊЕ ХИДРОГРАМА ОТИЦАЈА

Резиме: *Циљ серије испитивања започете 2015-е године у Хидрауличкој лабораторији Грађевинског факултета у Суботици је оспособљавање непотопљеног, оштроивичног прелива за мерење хидрограма отицаја. Суштина оспособљавања је фиксирање тачке налепљења и тачке одвајања. У односу на важећи међународни стандард ова тема је новост. У раније објављеним* *радовима овог аутора приказани су резултати вертикалног, несуженог, оштроивичног прелива различите висине P снабдевеног аератором звани вештачким прстом. У овом раду је приказан резултат испитивања за вертикални сужени прелив висине P=0.2 м.*

Кључне речи: *хидрограм, непотопљено преливање, оштроивични прелив, сужени прелив*