DIFFERENT HEIGHT THIN-PLATE WEIRS FOR MEASURING DISCHARGE HYDROGRAPHS

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Summary: *In 2015 it has been proven that the unsubmerged thin-plate weir of height equal 20 cm, with an artificial finger installed, is suitable for measuring flow hydrographs. The essence of fitting the weir for the task is fixing the discharges of adhesion and separation. This is an innovative statement comparing to the current ones of the international standards regarding thin-plate weirs. This paper presents the results of investigations carried out in the Hydraulic Laboratory of the Faculty of Civil Engineering in Subotica, Serbia, concerning measurements of flow hydrographs by the means of unsubmerged, full-width, thin-plate weirs of different height.*

Keywords: *thin-plate weir, free flow, height of the weir, flow hydrograph*

1. INTRODUCTION

The vertical, thin-plate, full-width weir of the height P is installed in the channel of rectangular cross sections of the width B. The angle between the crest line of weir and the direction of water flow in the canal is 90°.
During the non-submerged overflow, the water can flow by: a) aerated nappe, separated from the wall of the weir and b) non-aerated nappe, where the water flows adhered onto the weir [1]. Partially aeration of the weir stream affects the relationship between the flow rate Q and head of the nappe H [2-3]. The solution to this problem provides enabling of weirs for measuring discharge hydrograph. The essence of the enabling is fixing of the flow rate, in which there is the point of separation from the weir and fixing the flow rate, in which there is the point of adherence of the nappe [1].
Water flow in aerated overflow in the Republic of Serbia is calculated by the following equation:

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

where m is the discharge coefficient [1]. Generally, the discharge coefficient is the function m=f(H/P, H/B, We, Re), where We and Re are Weber and Reynolds numbers [1, 4-8]. The impact of these numbers on the discharge coefficient occur at low values of B, or H, or both B and H. For the calculation of Weber and Reynolds numbers, the more recent scientific literature uses the following terms $We=2\rho HB/\sigma$ and

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$Re=(2gH)^{0.5}(BH)^{0.5}/\upsilon$, where ρ is density, σ the surface tension coefficient and ν the kinematic viscosity coefficient of water [5, 7, 9].
Applicable international standard for determining the discharge coefficient in aerated nappe recommends two functions (Table 1).

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

Kindsvater-Carter	Rehbock
$m=\frac{\left(0.602+0.075\frac{H}{P}\right)\frac{2}{3}(B-0.0009)(H+0.001)^{\frac{3}{2}}}{B\cdot H^{\frac{3}{2}}}$	$m=\frac{\left(0.602+0.083\frac{H}{P}\right)\frac{2}{3}(H+0.0012)^{\frac{3}{2}}}{H^{\frac{3}{2}}}$
H≥0.03 m	0.03 m≤H≤1 m
P≥0.10 m	0.06 m≤P≤1 m
B≥0.15 m	B≥0.3 m
H/P<2.5	H/P≤4

Minimum head of aerated nappe is H=0.01 m – read in the paper of Gharahjeh et al. (2015) [7]. According to Bagheri et al. (2014) for the head of the overflow nappe H≥0.03 m influence of Weber and Reynolds numbers on the overflow is negligible [6]. Based on these recommendations, and those specified in Table 1, the limit of the head in respect to the impact of Weber and Reynolds numbers on the weir discharge is 0.01 m≤H≤0.03 m.
Seeking solution to this problem opened the examination intended to fix the point of separation and adherence: 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]. This conclusion has been confirmed in the Hydraulic Laboratory of the Faculty of Civil Engineering in Subotica, where the thin-plate weir of width B=0.1 m and height of P=0.2 m is 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. The horizontal part of the finger had to be installed at least Δz=0.016 m below the crest level. The point of separation occurs at flow rates Q=0.0004 m^3/s (H=0.0155↔0.0171 m), and point of adherence at flow rates Q=0.0002 m^3/s (H=0.01 m). The link between water flow and aerated nappe head is described by the functions given in the international standard. Of all these functions, the Rehbock function applies to increasing and reducing water flow at H/P≥0.1 (approximately H≥0.0171 m), and Kindsvater-Carter's function for reducing flow at 0.05≤H/P<0.01. 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. It was used in the derivation of the conclusions of the first examination on this issue – learned from the work of Zhang et al. (2010) [12]. Aeration of thin-plate weir width B=0.4 m and height P=0.341 m is executed by opening on both wall channels (openings were at half the height of weir located on the surface of the non-aerated nappe) and the pipeline. Point of separation of nappe was at H=0.034-0.036↔0.039-0.042 m, and the point of adherence at H=0.009 m. Knowledge of these points was important as for increasing overflow at the amount of overflow nappe 0.009 m<H≤0.034-0.036 m at non-aerated state for calculation of the discharge coefficient the proposed function was different from the function for H≤0.009 m. For thin-plate weir

equipped with artificial finger, the impact of Weber and Reynolds numbers on overflow is significant for increasing flow to the point of separation (H≤0.0155 m), and for decreasing flow from the adherence point (H≤0.01 m) [1]. 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: $$\frac{m}{m_{Rehbock}}=f\left(1000\left(\frac{We}{Re^2}\right)^{\frac{1}{3}}\right)=f\left(1000\left(\frac{\rho\nu^2}{\sigma H}\right)^{\frac{1}{3}}\right)$$

The height of weir does not affect the overflow of water for P≥0.1 m – read in the work of Bos (1989), Aydin et al. (2002) and Gharahjeh et al. (2015) [2, 4, 7]. These observations are based on a recommendation regarding the application of the formula for the calculation of the the discharge coefficient of aerated nappe by Kindsvater-Carter, used by international standard as well (Table 1). The aforementioned statements should be corrected: the formula of the discharge coefficient given by the standard applies to the height of weir P≥0.1 m, but at the same time – as seen in the formula – discharge coefficient is a function of the height of the weir. The aim of this study is to qualify the thin-plate, full-width, unsubmerged weir of the height P, equipped with artificial finger (Δz=0.016 m) for measuring discharge hydrographs.

2. TEST RIG DESCRIPTION

In the Hydraulic Laboratory of the Faculty of Civil Engineering in Subotica, thin-plate, full-width weir is installed on the downstream end of the channel of width B=0.1 m length 2.2 m (Figure 1).

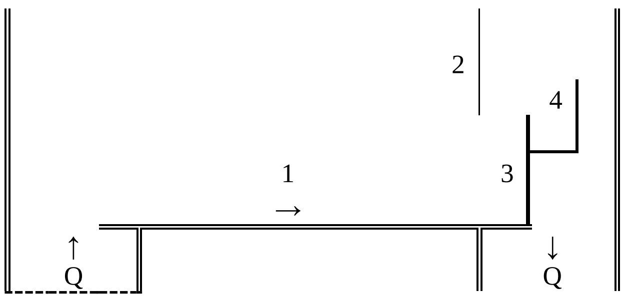

Figure 1 Experimental installation
1 – channel width B, 2 – gauge, 3 – thin-plate weir of the height P, 4 – artificial finger

The height of the weir was 0.1, 0.15 and 0.2 m.

Artificial finger with the aforementioned characteristics was located at half the width of the weir with the displacement angles between the crest of the weir and the horizontal part of the artificial finger Δz=0.016 m. Unlike the tests whose results were published in 2016, these tests determined the distance of constant width δ=1.5 mm between the horizontal arm of artificial finger and downstream side of thin-plate weir [1]. This spacing provided sufficient supply of air for simultaneous nappe aeration.
All other conditions of investigation were equal to those described in paper published in 2016 [1]. Water from the reservoir was brought to the channel with the pump, and after a free spill over, it was either returned to the reservoir, or was diverted to an intake vessel for measurement purpose. 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).
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.
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 19.8^{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 MEASUREMENTS

For weirs of a height of 0.1, 0.15 and 0.2 m testing was performed in aerated, partially aerated and non-aerated state of overflow nappe (Table 2).

Table 2 Number of aerated, partially aerated and non-aerated states of weirs in the examined overflows

Height od weir P (m)	*Number of aerated state*	*Number of partially aerated state*	*Number of not-aerated state*
0.10	*33*	*-*	*26*
0.15	*45*	*5*	*39*
0.20	*40*	*-*	*43*

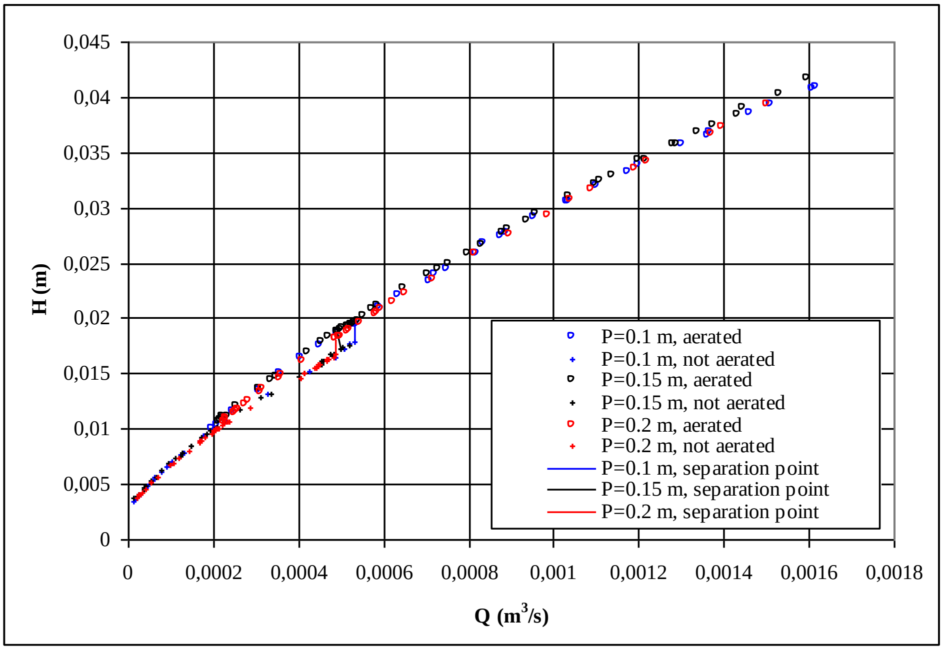

Figure 2 Relationship between the head the overflow nappe H and water flow Q for full-width weir of a height of 0.10, 0.15 and 0.20 meters

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 ventilated at the beginning, while later on the nappe got separated from the plate. At a certain flow rate of water, there is a point of separation of the nappe. In the opposite trend with a certain flow rate, the nappe adhered onto the weir. This is the point of adherence of the nappe. Regardless of the height of the weir, point of adherence was stable: it occurred at H=0.01 m.

Table 3 Discharges and head of the overflow nappe of the separation point for testing the height of the overflow

Height od weir P (m)	*Discharge Q*	*Head of the overflow nappe H (m)*	*Head of the overflow nappe H (m)*
(m)	*(m^3/s)*	*Non-aerated states*	*Aerated states*
0.10	*0.00053*	*0.0178*	*0.0194*
0.15	*0.00050*	*0.0172*	*0.0188*
0.20	*0.00049*	*0.0167*	*0.0182*

Out of all measurements, the states with aerated nappe were singled out, thus on the basis of equation (1) the calculated discharge coefficients (Figure 3).

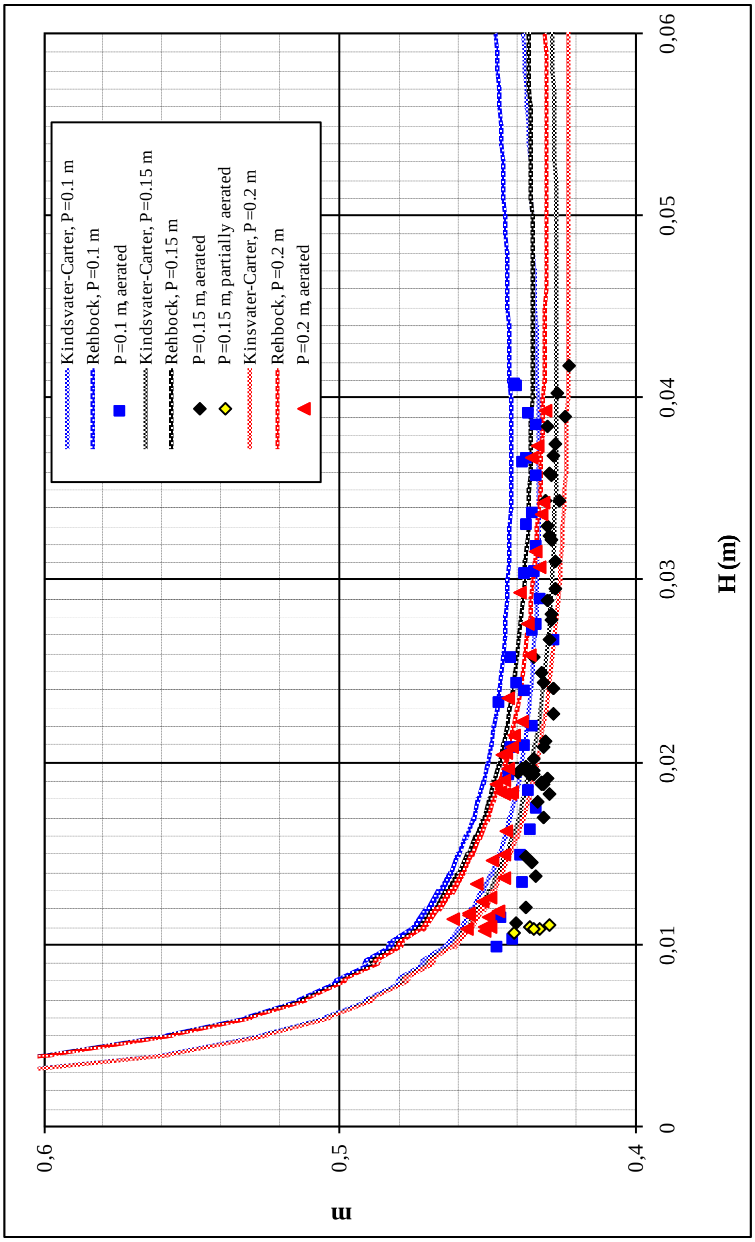

Figure 3 Discharge coefficient of aerated nappe m as a function of the head of the overflow nappe H for tested heights of the weir

For non-aerated nappe for testing the height the weir are given in two versions (Figures 4 and 5):

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

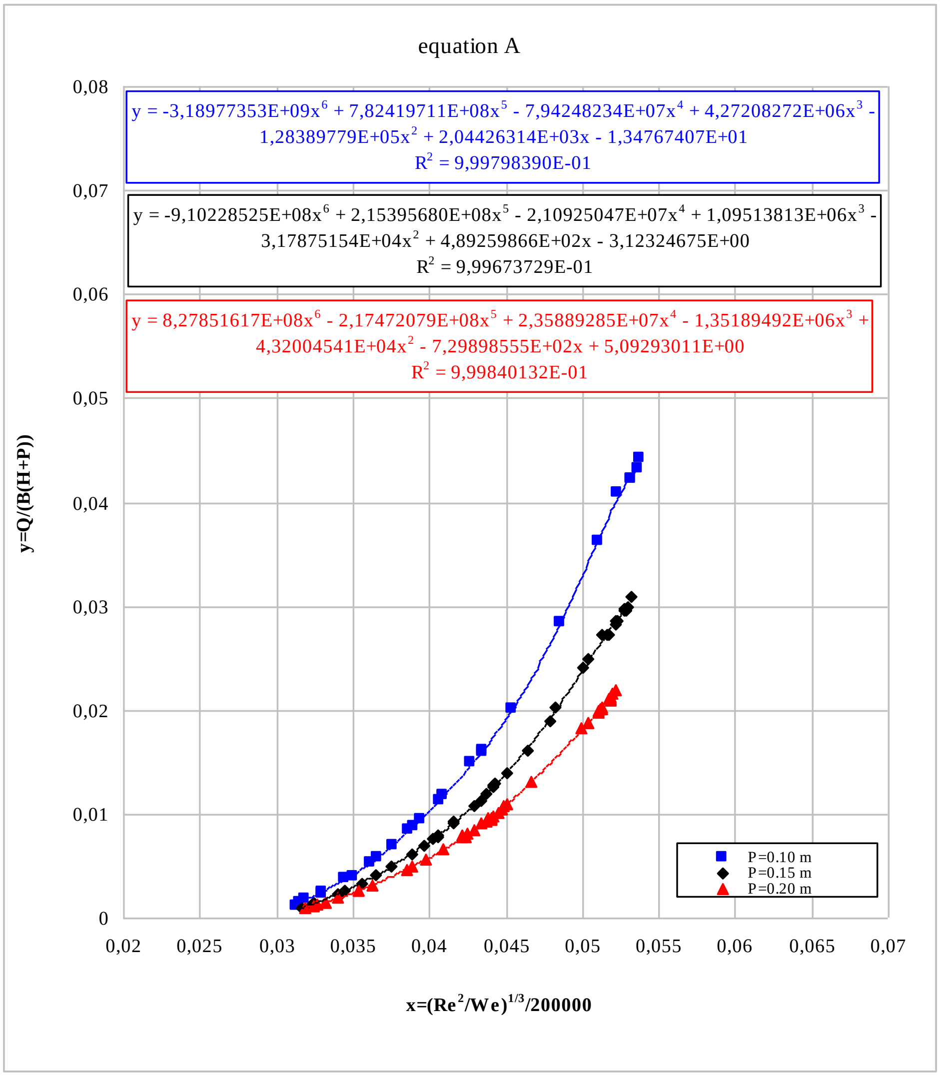

Figure 4 Function $\frac{Q}{B(P+H)}=f\left(\left(\frac{\sigma H}{\rho v^2}\right)^{\frac{1}{3}}\frac{1}{20000}\right)$ *for non-aerated overflow nappe for tested heights of the weir*

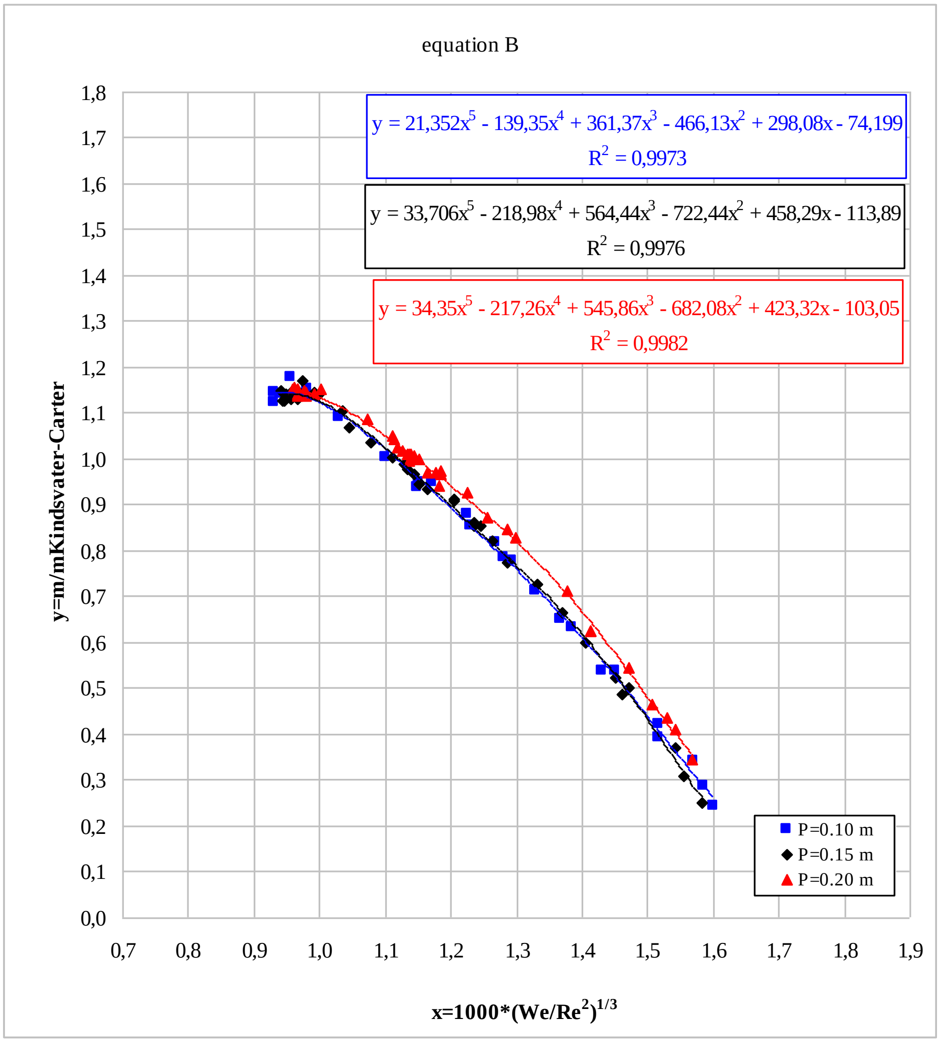

Figure 5 Function $\frac{m}{m_{\text{Kindsvater-Carter}}}=f\left(1000\left(\frac{\rho v^2}{\sigma H}\right)^{\frac{1}{3}}\right)$ *for non-aerated overflow nappe for tested heights of the weir*

4. DISCUSSION

1. Using artificial finger (for Δz=0.016 m and δ=1.5 mm) aerated nappe flow occurs: for increasing flow at the head of the overflow nappe H≥0.0194 m (for P=0.10 m), H≥0.0188 m (for P=0.15 m) and H≥0.0182 m (for P=0.20 m), and for reduced flow at H≥0.01 m.

International standard gives two equations for calculation of discharge coefficients in aerated state of the overflow. According to Figures 3 and 6, the results of measuring discharge coefficient are most consistent with the values of equations:

- according Kindsvater-Carter for the entire test range (for P=0.10 and 0.15 m), i.e. for 0.01 m≤H≤0.0182 m (for P=0.20 m), and
- according to Rehbock for 0.0182 m<H<0.04 m (for P=0.20 m).

Their border is about the separation point of the nappe from the weir.

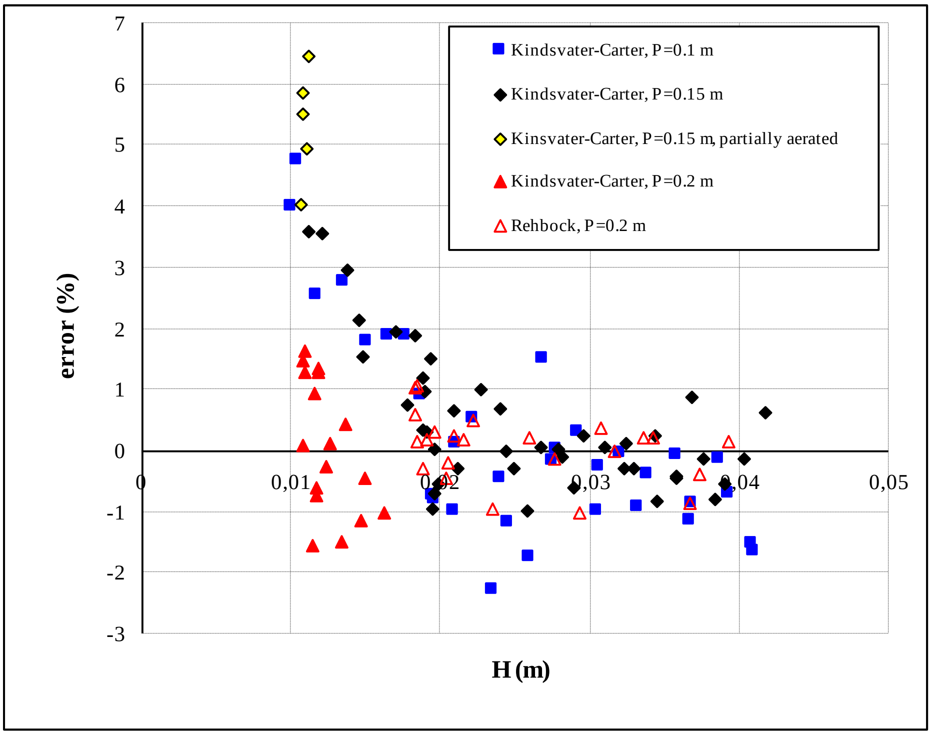

Figure 6 Error of discharge coefficient m as a function of the head H for the overflow nappe for thin-plate weir (aerated jet) of the tested height

Errors of 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 the range 0.01 m≤H≤0.0182 m calculated according to Kindsvater-Carter are between -1.5 and +1.6% and for the range 0.0182 m<H<0.04 m according to Rehbock are between -1 and +1.1% for P=0.20 m (Figure 6). Moving closer to the adherence point, error of discharge coefficient increases.

When using this weir for flow measuring, one should check which equation of the international standard should be used for calculating the discharge coefficient in aerated nappe in the specific case. This check is extremely important, as the result depends a lot on the accuracy of the derived condition of the crest, on the accuracy of measurements of the head of the overflow nappe and on the accuracy of determining the crest level of the weir.

2. Since these functions do not depend on the Reynolds and Weber numbers, unlike the professional literature, the impact of these numbers can be reduced from H≥0.03 m:

- to H≥0.0194 m (for P=0.10 m), H≥0.0188 m (for P=0.15 m) and H≥0.0182 m (for P=0.20 m) for the increasing flow, or
- to H≥0.01 m for the decreasing flow.

3. Partially aerated overflow occurs near the point of adherence, for H≤0.0011 m (Figures 3 and 6). Errors of discharge coefficient at this state is between +4 and +6.5% (for P=0.15 m). In accordance with the approach of professional literature, in partially aerated nappe, the error of discharge coefficient is significant. The impact of this phenomenon on the error of flow determination will become visible, when the accuracy of measurement of water level on the catchments reaches the accuracy level of measurements in the laboratory.

4. In case of 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 water flow (variant A), or discharge coefficient (variant B) is (Figures 7 and 8):

- 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) in 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) in variant B.

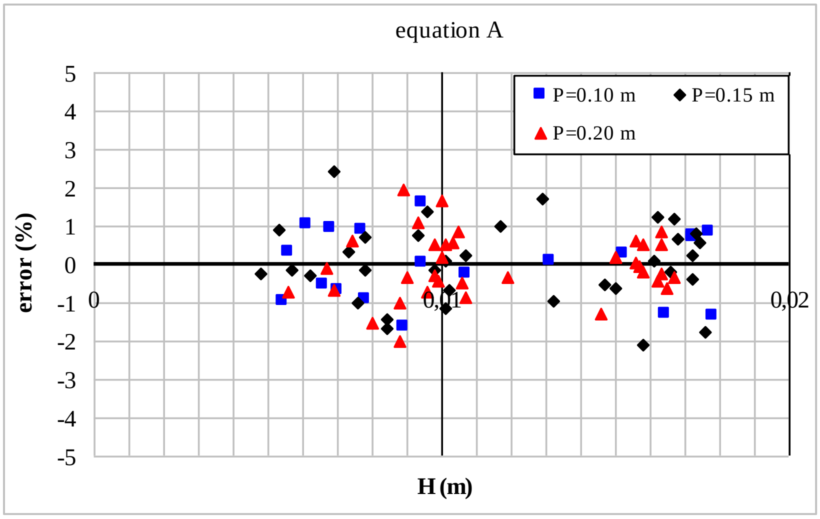

Figure 7 Error of determination of flow Q as a function of the head of the overflow nappe H for thin-plate weir (non-aerated nappe) of the tested height

In accordance with the conclusion published in 2016 and in this case the following applies [1]: in the non-aerated nappes, the use of artificial finger improves the identification of the flow rate in the variant A – errors were between -2.1 and + 2.4%. To achieve the specified measurement accuracy for non-aerated overflow in the specific case as well, the equation shown in the Figure 4 should be firstly determined in laboratory.

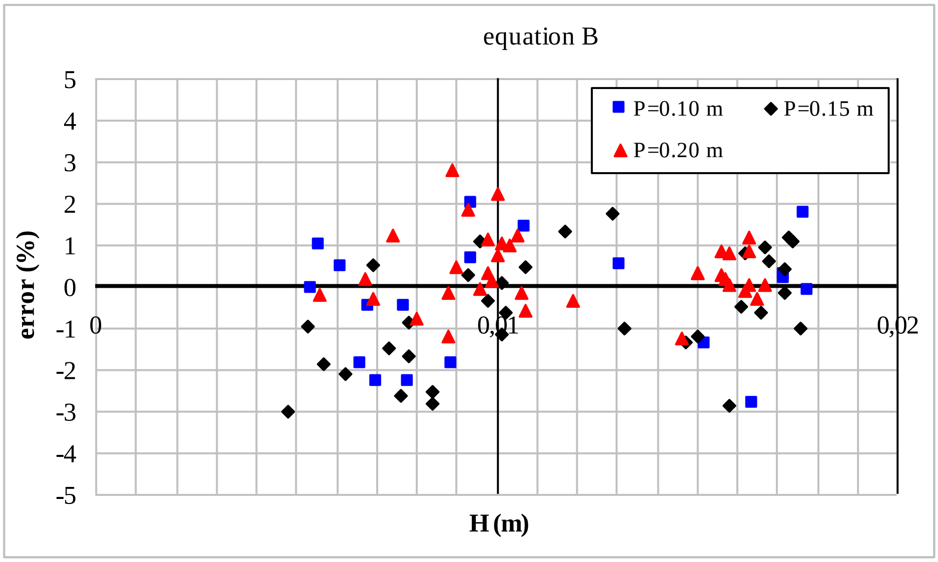

Figure 8 Error of determination discharge coefficient m as a function of the head of the overflow nappe H for thin-plate weir (non-aerated nappe) of the tested height

5. CONCLUSION

When using artificial finger (Δz=0.016 m and δ=1.5 mm) at full-width thin-plate weir at different weir heights, the point of adherence is at the same head of the nappe, and the flow rate of separation point decreases with increasing weir height. Artificial finger aerates the water nappe for the increasing flow in H≥0.0194-0.0182 m, and for decreasing overflow at H≥0.01 m. Reynolds and Weber numbers do not affect these heads of the overflow nappe to the overflow. Artificial finger enables the measurement of discharge hydrograph in unsubmerged weirs on thin-plate, full-width weir of different heights:

- in aerated nappe, by using the function of international standard, the water flow can be determined by errors between -2.3 and +4.8%, and
- in non-aerated jets H≥0.0048-0.0053 m by using a prescribed function in the Figure 4 the water flow can be determined by errors between -2.1 and +2.4%.

Due to the sensitivity of results to the accuracy of derived state of the crest, to the accuracy of measurement of head of the overflow nappe and the accuracy of determining the crest level of the weir before using this weir in the particular case, the equations which calculate the water flow should be firstly determined for both cases, in the laboratory.
Further research should determine the location of the artificial finger in case of the contracted thin-plate weir (where the width of the weir is less than the width of the channel) at unsubmerged, aerated overflow in the function of degree of weir-contraction.

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OŠTROIVIČNI PRELIV RAZNE VISINE ZA MERENJE HIDROGRAMA OTICAJA

Rezime: *Za oštroivični, nepotopljeni preliv visine 20 cm 2015-e godine je dokazan da korišćenjem veštačkog prsta preliv je osposobljavanje za merenje hidrograma oticaja sa sliva. Suština osposobljavanja je fiksiranje proticaja za tačku odvajanja od zida preliva i za tačku nalepljenja na zid preliva. Ova konstatacija je novina u odnosu na navode postojećeg međunarodnog standarda u vezi oštroivičnog preliva. U ovom radu su prikazani rezultati ispitivanja izvršene u Hidrauličkoj laboratoriji Građevinskog fakulteta* *u Subotici (Republika Srbija) u vezi merenja hidrograma oticaja nepotopljenim, nesuženim, oštroivičnim prelivima razne visine.*

Ključne reči: *oštroivični preliv, nepotopljeno prelivanje, visina preliva, hidrogram oticaja*