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Practical aspects of the use of the sluice gate discharge equations to estimate the volumetric flow rate in the irrigation channels

Elżbieta Kubrak[1], Janusz Kubrak[2]

[1] Warsaw University of Life Sciences – SGGW, Water Center, Warsaw, Poland

[2] Warsaw University of Life Sciences – SGGW, Faculty of Civil and Environmental Engineering, Nowoursynowska 166, 02-787 Warsaw, Poland

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Abstract: The article presents the experimental results of the calibration of the typical check structure with sluice gates installed in a trapezoidal irrigation channel. Hydraulic experiments on sluice gate discharge capacity were performed on a model made in a 1:2 scale. It has been explained how the method of measuring the downstream water depth below the sluice gate in the check structures installed in a trapezoidal irrigation channels affects the measured depth values. On the basis of hydraulic measurements, regression relationships were developed for the discharge coefficients for submerged outflow through the sluice gate in two types of sluice gates installed in irrigation channels. The formulas allow to calculate the volumetric flow rate below the submerged sluice gate after determining the water depth upstream and below the sluice gate and the gate opening height. The differences in volumetric flow rates calculated from regression relationships and measured values do not exceed 10%, which confirms their practical suitability for calculating the discharge through a sluice gate mounted in a trapezoidal channel. The values of the discharge coefficients determined in the channels with rectangular cross-sections are not useful for the discharge coefficients of sluice gates check structures installed in trapezoidal channels. Nomograms and relationships for discharge coefficients of the analysed sluice gate were developed.

Keywords: discharge coefficient, error of discharge calculation, irrigation channel, laboratory model investigations, submerged sluice gate flow, volumetric flow rate

INTRODUCTION

Rational management of limited water resources requires the measurement of the flow rate of water supplied and used in irrigation and the regulation of water levels in irrigation canals and watercourses included in the drainage systems. Today, the world's irrigation systems are equipped with modern, electronically controlled devices for measuring the flow rate and regulating water levels. In existing irrigation systems, a desirable solution is to adapt existing structures to measure the flow rate of the supplied water. An overview of the structures and devices used to measure the volumetric water flow in irrigation canals can be found, among others in the work edited by Kaca and Kubrak (eds.) [2020]. Hydraulic research on determining the capacity of the dock sluice gate used in irrigation systems has already been undertaken [Jędryka, Kaca 1998]. The check structure is a small damming structure with a flat, vertical sluice gate installed in the recesses. Depending on the way the recesses are arranged, they may or may not contract the stream cross-section.

The sluice gate flow has been the subject of numerous theoretical studies, laboratory and field works focused on the flow measurements and flow control [Boiten 1992; Clemmens *et al.* 2003; Jędryka, Kaca 1998; Kaca 1996; Kraatz 1975; Kubrak *et al.* 2020; Lozano *et al.* 2009; USBR 2001]. The sluice gates are usually installed in irrigation channels. The rectangular gate is located in trapezoidal channel. The geometry of the channel is complex and influent on outflow conditions from sluice gate. This type of gate is widely used in the irrigation canals of Poland. Design solutions used, i.e. a rectangular gate in a trapezoidal channel do not allow for the direct use of the value of discharge coefficients to calculate the outflow from available standard formulas given in hydraulic books, water management manuals and papers [KUBRAK *et al.* 2020]. Due to the difficulties associated with calibration of such sluice gates in the field, a laboratory method of hydraulic experiment was chosen to determine their throughput. Based on the conducted hydraulic laboratory tests, the flow rates of such gates were determined [KUBRAK, KUBRAK 2020]. During the research, attention was drawn to the problem of measuring the water depth below the gate, used to assess the capacity of the sluice gate. On the basis of the collected research results, dependencies were developed that were adapted to be used in practice.

STUDY METHODS

ANALYTICAL EQUATIONS DESCRIBING A FLOW THROUGH THE SLUICE GATE

Depending on the downstream water level in relation to the edge of the gate, the flow can be free or submerged. Free outflow – unsubmerged – appears when the downstream water does not affect the upstream water level. This form of the flow occurs in irrigation channels usually shortly after opening the sluice gate and quickly turns into the submerged flow. Submerged flow means that downstream water exceeds the edge of the gate and have an effect on the water level upstream the gate. In submerged outflow of the sluice gate, a hydraulic jump occurs just downstream the gate, as shown in Figure 1a, when the water depth h_z right next to the gate is clearly smaller than the downstream water depth h ($h_z < h$) or in the case of the submerged jump (Fig. 1b), when the water depth at the gate is close to the downstream water depth ($h_z \approx h$).

Due to the variability of the bottom water depth profile, the relationship given by ROUSE [1946] is more often used to determine the rate of water outflow from the vertical sluice gate with a submerged outflow:

$$Q = C_d ab\sqrt{2gH} \tag{1}$$

where: C_d = the discharge coefficient (–) in Equation (1), a = gate opening (m), b = width of sluice gate (m), g = gravitational acceleration (m·s^{-2}), H = upstream water depth (m).

According to SWAMEE [1992], the submerged flow under the sluice gate appears when the condition (Fig. 1b) is met:

$$H < 0.81h\left(\frac{h}{a}\right)^{0.72} \tag{2}$$

SWAMEE [1992] developed regression dependencies in the function of the measured quantities upstream H and downstream h depths, and gate opening height a for the discharge coefficients C_d determined on the basis of the results of research carried out for the unsubmerged and submerged sluice gate outflow published by HENRY [1950] and then confirmed by RAJARATNAM and SUBRAMANYA [1967]. In the case of unsubmerged outflow under the sluice gate, the discharge coefficients depend on the upper water depth H and the of the sluice gate opening a. However, in the case of submerged outflow, it is necessary to link them with the downstream water depth h. However, there are no clear recommendations in the literature regarding the place and method of measurement the downstream water depth h used to determine the discharge coefficients for the submerged sluice gate outflow.

Additionally, the comparative analyses of the discharge coefficients for the submerged outflow from the sluice gate, determined from the SWAMEE [1992] dependence and from the laboratory hydraulic measurements, showed that they cannot be used to determine the discharge of the sluice gate installed in the check structure. Their possible use requires the use of corrections given in the work of KUBRAK *et al.* [2020].

The article presents guidelines for measuring the downstream water depth and the relationships for determining the volumetric flow rate for the submerged outflow from the sluice gate in practice.

EXPERIMENTAL TESTS OF SUBMERGED FLOW OF THE SLUICE GATE IN A DOCK CHECK

Hydraulic experiments of the discharge capacity of the sluice gate model placed in the trapezoidal channel (Photo 1) were carried out in the hydraulic laboratory of the Faculty of Civil and Environmental Engineering of the Warsaw University of Life Sciences (Pol. Wydział Budownictwa i Inżynierii Środowiska Szkoły Głównej Gospodarstwa Wiejskiego w Warszawie). The sluice gate model was built in a scale of 1:2 in relation to the prototype structures used in practice [CBSiPWM 1969]. It should be noted, that it is impossible to maintain complete dynamic similarity from the prototype to the model the sluice gate model

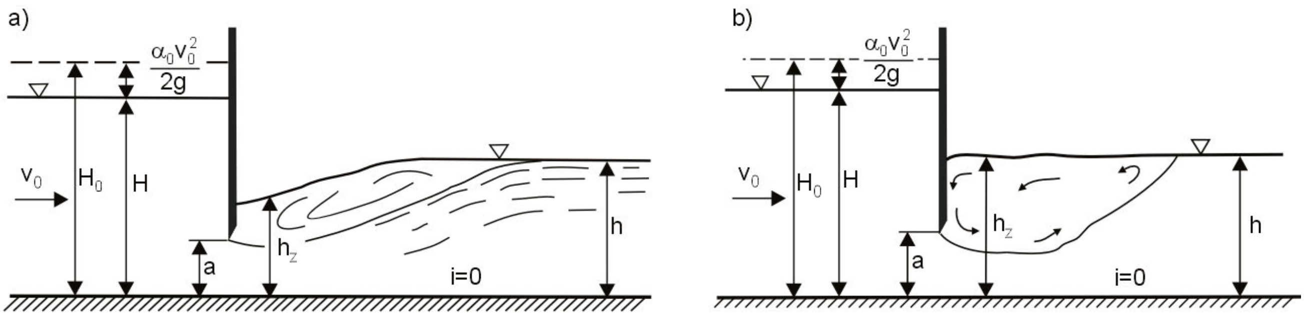

Fig. 1. Submerged flow through the sluice gate: a) $h_z < h$, b) $h_z \approx h$ the tailwater curve is always above the jump curve: h_z = the depth near the sluice gate (m); a = gate opening (m), g = gravitational acceleration (m·s^{-2}), H_0 = total head upstream (m), H = upstream water depth (m), h = downstream water depth (m), i = slope of the bottom (–), v_0 = average flow velocity upstream from gate (m·s^{-1}); v_1 = average flow velocity (m·s^{-1}); v = average flow velocity downstream from gate (m·s^{-1}); α_0, α_1 = velocity distribution coefficient (–); source: own elaboration

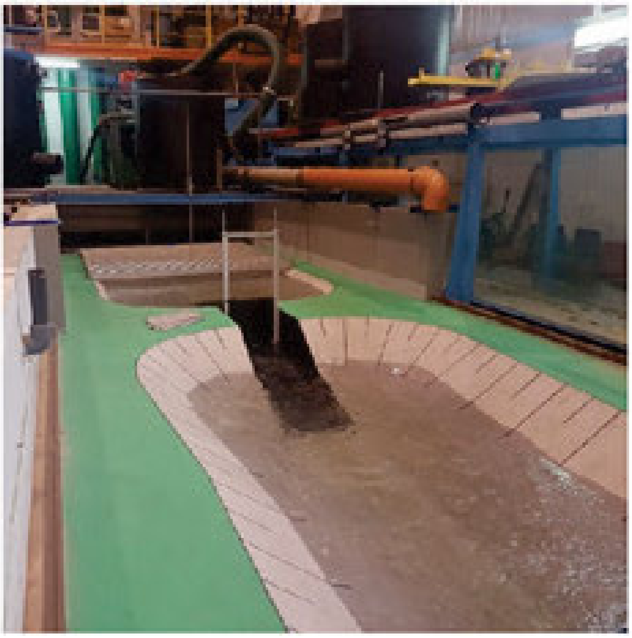

Photo 1. Experimental setup – view from the downstream side (phot. *Z. Pietraszek*)

was large enough so that surface tension and viscosity effects are minimal to avoid scale effects.

The sluice gate model was supplied from a closed water circuit in the hydraulic laboratory. The water flow rate was measured with an induction flow meter installed on the supply pipeline. The conditions of water flow in the channel downstream the sluice gate was controlled by adjusting the downstream water depth, with an overflow gate installed at a distance of 3.20 m downstream the sluice gate. This way it was possible to model the changing flow conditions, caused in practice by an increase in the flow resistance in the channel due to the growth of vegetation. After stabilisation of the water levels on both sides of the sluice gate, the water depths along the axis of the channel in the upper and lower stands were measured with the use of pin water gauges equipped with sound signalling devices, which, upon a contact with water, sent an acoustic signal. The downstream water depths for the flow rate were measured in the cross section located at a distance of 3.035 m downstream the sluice gate [KUBRAK, KUBRAK 2020], and the water depth in the upper stand at a distance of 2.0 m of the sluice gate front (Fig. 2). Independently, the water profile downstream the gate was acquired using the pin gauge and a piezometer in the channel axis.

In order to investigate the hydrostatic pressure on the bottom of channel pressure transmitter PNEFAL 1151DP was used. A static calibration test was carries out in order to convert voltage signal to the pressure. The linear equation was determined from the static calibration test using different flow depths. The pressure values were recorded every 0.4 s. The average pressure value was calculated on the basis of 1000 instantaneous measurements.

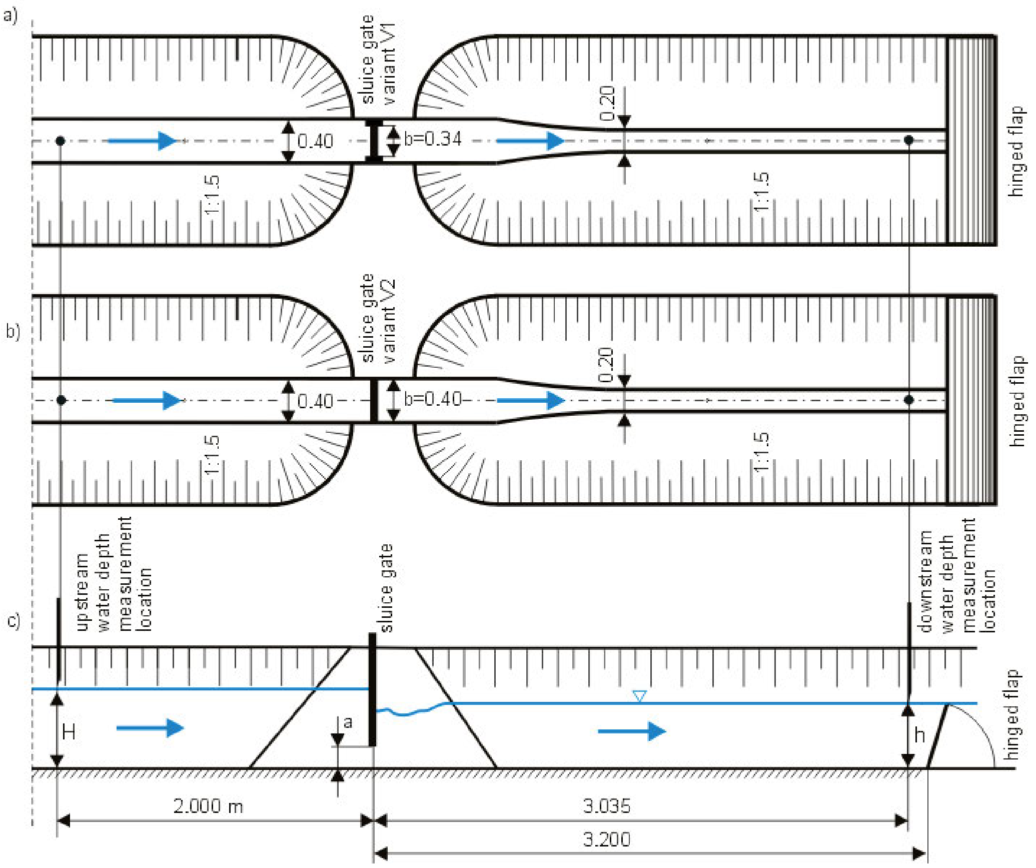

Fig. 2. Scheme of the top view of the sluice gate model with the location of depth measurement points (dimensions are given in metres): a) variant 1, b) variant 2, c) longitude profile of the check structure; source: own elaboration

Two variants of the research were carried out in order to analyse the discharge capacity. In variant 1 (V1), the sluice gate was moved in guides which narrowed the rectangular section of the 0.40 m opening to b = 0.34 m (Fig. 2a). In variant 2 (V2), the gate was moving in guides mounted in the wall of the abutments in such a way that the guides did not reduce the width of the opening and b = 0.40 m (Fig. 2b).

Measured water depths of upstream H and downstream h were used to calculate the discharge coefficients for the submerged flow under the gate. Depth measurements were made at gate openings $a \in (0.031; 0.101)$ m and flow rates $Q \in (0.0107; 0.0510)$ $m^3 \cdot s^{-1}$. In the variant 1, 400 experiments were performed and in variant 2, 1200 experiments were performed.

RESULTS AND DISCUSSION

MEASUREMENTS OF THE WATER DEPTHS DOWNSTREAM THE SLUICE GATE

In the performed hydraulic experiments, the water depth downstream the gate was measured with a pin water gauge and a piezometer along the channel axis. The profiles of the water levels downstream the sluice gate measured in this way are shown in Figure 3. Figure 3 shows that the greatest differences in the water depths were recorded near the sluice gate and reached even 12%, and then gradually decrease with an increasing distance. In the measurement sections located more than 2 m downstream the gate there were no differences in the measured water depth.

Measuring the water depth with a piezometer is used in streams with hydrostatic pressure distribution. The compatibility of the water depths measured with both methods means that there is a hydrostatic pressure distribution in the cross-section. As shown in Figure 3, this cross-section is located 2 m from the cross-section of the sluice gate and is located in the trapezoidal channel. In the experiments of the capacity of the submerged outflow through sluice gate, the depth was measured with a point gauge in a cross-section distant from the gate by 3.5 m. In practice, the measurement of the water depth downstream the sluice gate is performed using a water gauge or piezometers wells. The cross-section for the depth measurement should be in the cross-section with the hydrostatic pressure distribution.

DISCHARGE COEFFICIENTS FOR THE SUBMERGED FLOW UNDER THE SLUICE GATE IN CHECK STRUCTURE

The discharge coefficients for the submerged flow through the sluice gate used to calculate the discharge depend, on the basis of the dimensional analysis, on the dimensionless ratios of hydraulic parameters [OSKUYI, SALMASI 2012]:

$$C_d = f\left(\frac{h_z}{a}, \frac{H}{a}, \frac{h}{a}, \frac{1}{(\mathrm{Fr})^2}\right) \tag{3}$$

where: Fr = the value of the Froude number in the rectangular section below the sluice gate (ba).

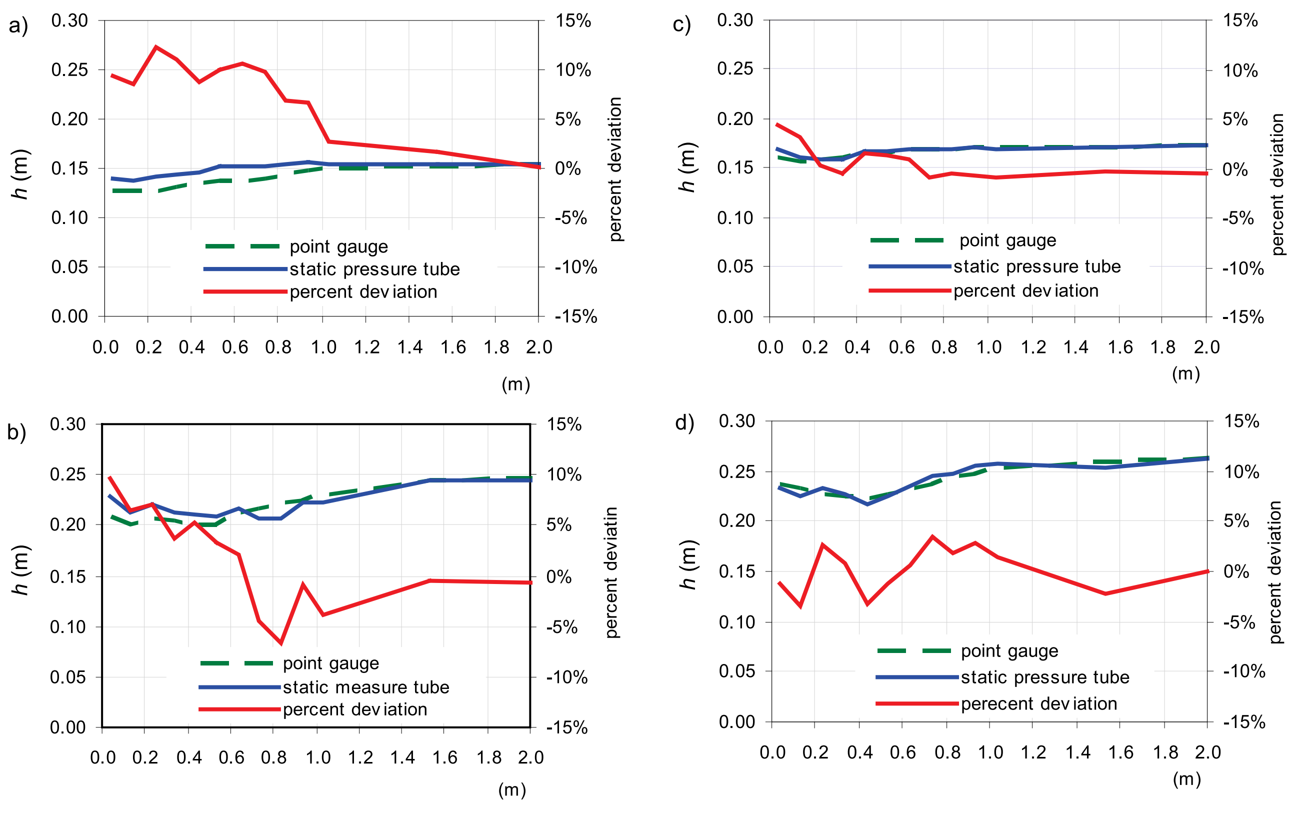

Fig. 3. Percentage deviations of the depths (h) measured with a piezometer in relation to the depths measured with a pin gauge at the different opening of the sluice gate (a) and in different discharge (Q) conditions: a) a = 0.06 m, Q = 0.0105 $m^3 \cdot s^{-1}$, b) a = 0.06 m, Q = 0.0243 $m^3 \cdot s^{-1}$, c) a = 0.08 m, Q = 0.0119 $m^3 \cdot s^{-1}$, d) a = 0.08 m, Q = 0.0269 $m^3 \cdot s^{-1}$; source: own study

In Equation (3), the dimensionless ratio containing the Froude number is calculated for the measured discharge Q:

$$\frac{1}{(\mathrm{Fr})^2} = \frac{1}{\left(\frac{Q/ba}{(ga)^{0.5}}\right)^2} \tag{4}$$

The discharge coefficients determined in both test variants are presented as a function of the Froude number for specific ratios of the downstream water $C_d = f\left(\frac{1}{(\mathrm{Fr})^2}, \frac{h}{a}\right)$ depth to the gate opening in Figure 4.

In the cross-section of the sluice gate the subcritical flow is by submerged flow through sluice gate present (Fr < 1), when the value of $1/\mathrm{Fr}^2 > 1$. Figure 4 shows that in variant 1, in which the sluice gate opening is narrowed by guides (side throttling).

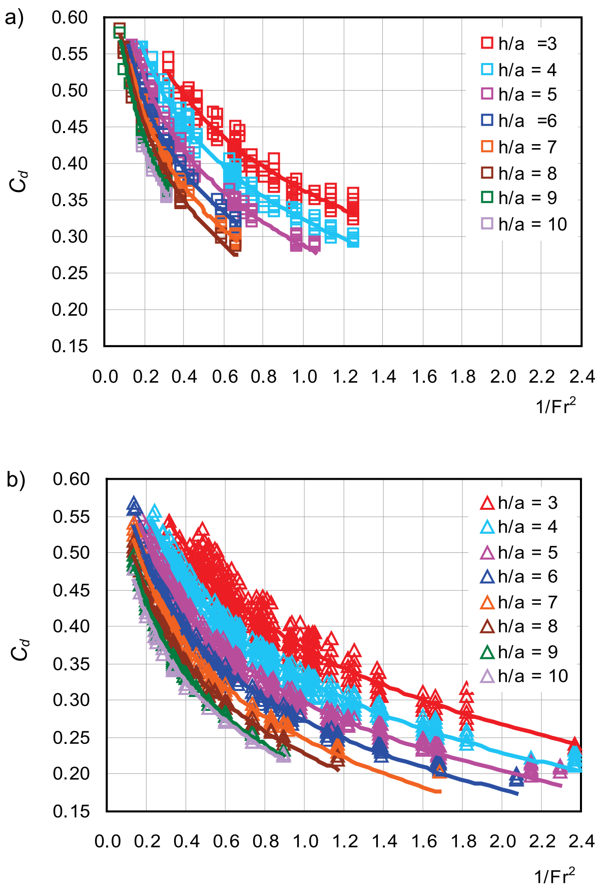

Fig. 4. Discharge coefficients (C_d) as a function of Froude number (Fr) $C_d = f\left(\frac{1}{(\mathrm{Fr})^2}, \frac{h}{a}\right)$ in investigated variants: a) V1, b) V2; h = downstream water depth, a = gate opening; source: own study

This occurs when there is a slight difference in depth between the upstream and downstream water dept (low hydraulic slope). Figure 4 shows that in variant 1, in which the light in the cross-section of the gate is reduced by guides (side throttling), the subcritical flow occurs only at "large" openings of the gate in relation to the bottom water depth $h/a = 3$, $h/a = 4$ and $h/a = 5$. In variant 2, the subcritical flow in the section of the gate occurs at $h/a = 3$, $h/a = 4$, $h/a = 5$, $h/a = 6$. With the ratio $h/a = 7$ and $h/a = 8$, the subcritical flow in the cross-section of the sluice gate occurs in individual cases, and with ratios $h/a = 9$ and $h/a = 10$, that is, for "small" heights of the gate valve opening, and in the cross-section there is supercritical flow.

The relationships in Figure 4 are linear on a logarithmic scale (Fig. 5).

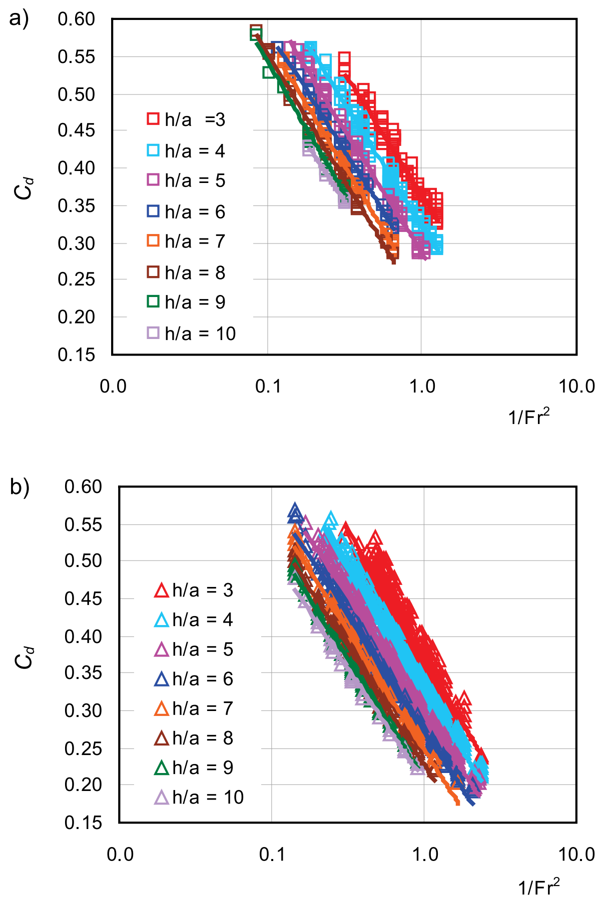

Fig. 5. Discharge coefficients (C_d) for submerged flow through the sluice gate as a function of Froude number (Fr) and downstream depth (h) to gate opening ratio $C_d = f\left(\frac{1}{Fr^2}, \frac{h}{a}\right)$ in investigated variants: a) V1, b) V2; a = gate opening; source: own study

The form of flow in the cross-section of the sluice gate, apart from the gate, is influenced by the upstream and downstream water depths and gate opening height. The total influence of all these elements is captured by the quotient of the depths difference to the gate opening of the sluice gate (Fig. 6).

As shown in Figure 6, there is a very strong relationship between the discharge coefficient C_d and the form of flow in the cross-section of the sluice gate. In turn, the form of water flow is very strongly related to the ratio of the difference of the depths to the opening of the sluice gate, i.e. directly measured parameters. Therefore, the discharge coefficients C_d for the submerged flow through the sluice gate depend on the ratio of the difference of the depths of water to the gate opening and the ratio of the downstream depth to the gate opening $C_d = f\left(\frac{H-h}{a}, \frac{h}{a}\right)$.

The linear dependencies in Figure 7 was described with the regression equations in the form:

$$C_{dc} = x \ln\left(\frac{1}{\frac{H-h}{a}}\right) + y \tag{5}$$

where: x, y = coefficients of the regression function depending on the difference upstream and downstream depths $(H - h)$ to opening height of the sluice gate h/a.

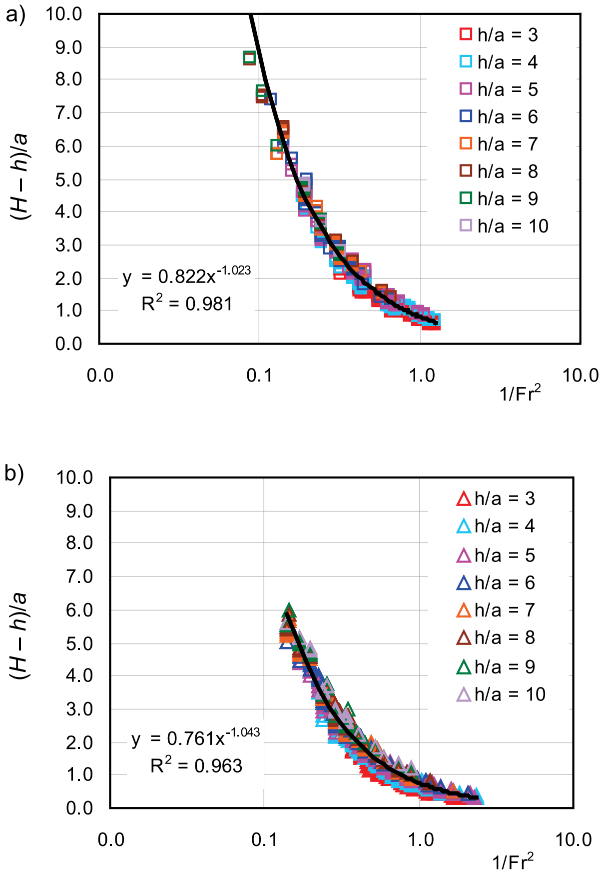

Fig. 6. The dependence of the form of flow in the cross-section of the sluice gate on the ratio difference of the upstream and downstream water depths $(H - h)$ to the opening of the sluice gate (a) $\frac{1}{Fr^2} = f\left(\frac{H-h}{a}\right)$; source: own study

The parameter x in Equation (5) was expressed as a linear relationship with respect to h/a. The parameters y in Equation (5) was expressed as a quadratic relationship with respect to h/a, and the Froude number was characterised by ratio $\frac{H-h}{a}$, and on this basis, regression relationships for the sluice gate discharge coefficients were constructed $C_{dc} = f\left(\frac{H-h}{a}, \frac{h}{a}\right)$:
for variant V1:

$$C_{dc} = \left(0.0051\frac{h}{a} + 0.1194\right)\ln\left(\frac{H-h}{a}\right) + 0.0024\left(\frac{h}{a}\right)^2 + \\ - 0.0635\frac{h}{a} + 0.5688 \tag{6a}$$

for variant V2:

$$C_{dc} = \left(0.0019\frac{h}{a} + 0.1273\right)\ln\left(\frac{H-h}{a}\right) + 0.0031\left(\frac{h}{a}\right)^2 + \\ - 0.0718\frac{h}{a} + 0.6114 \tag{6b}$$

Discharge coefficients C_d obtained from the measurements and the calculated C_{dc} from the Equations (6a) and (6b) are presented in Figure 7.

The percentage deviations ΔC_d of the values of the discharge coefficients C_d obtained from the measurements and the calculated C_{dc} using the Equation (6a) in the variant 1 and (6b) in the variant 2 were showed on Figure 8.

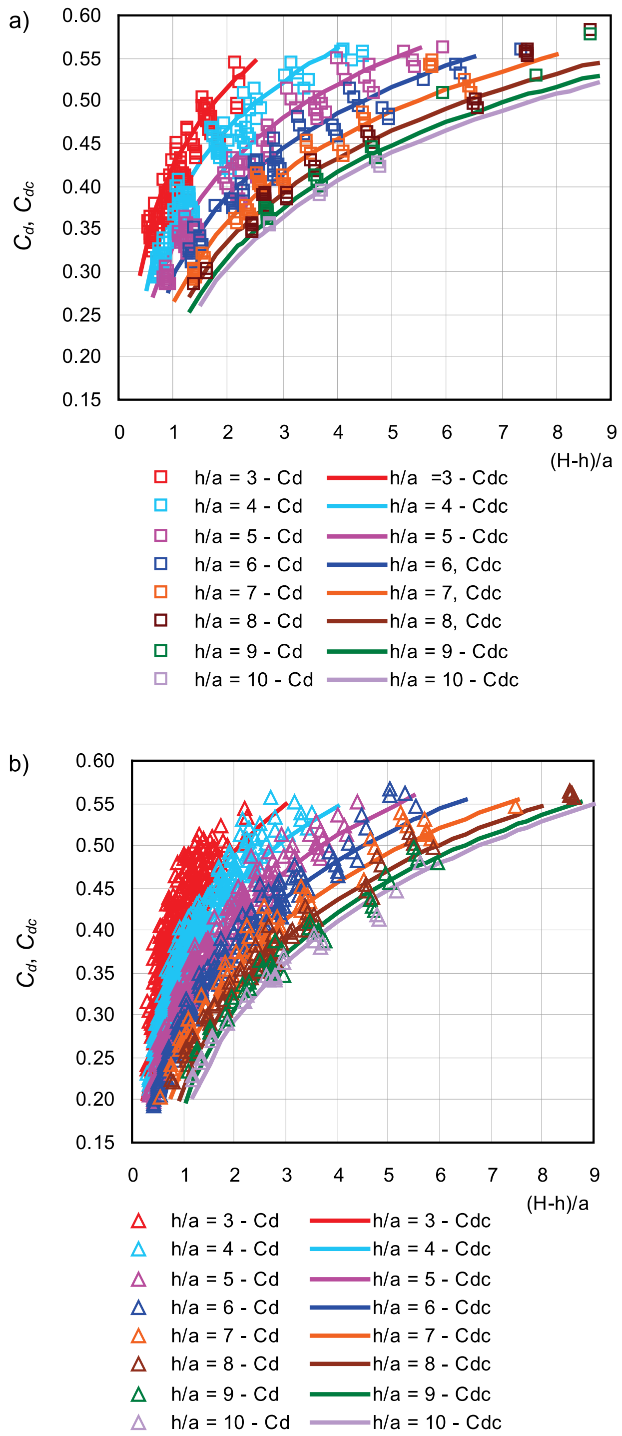

Fig. 7. Discharge coefficients as a function of the ratio of difference depths to the sluice gate opening $(H - h)/a$ and the water depth downstream to gate opening h/a obtained from the measurements of discharge coefficient (C_d) and calculated discharge coefficient (C_{dc}): a) from the Equation (6a) for the variant V1, b) from the Equation (6b) for the variant V2; source: own study

The discharge coefficients calculated from the Equations (6a) and (6b) differ from those calculated on the basis of measurements by $\Delta C_d = \pm 10\%$. Therefore, the Equations (6a, 6b) based on dimensionless ratios $C_{dc} = \left(\frac{H-h}{a}, \frac{h}{a}\right)$ can be useful in practice for determining the flow coefficients of sluice gates used in irrigation channels (Fig. 9).

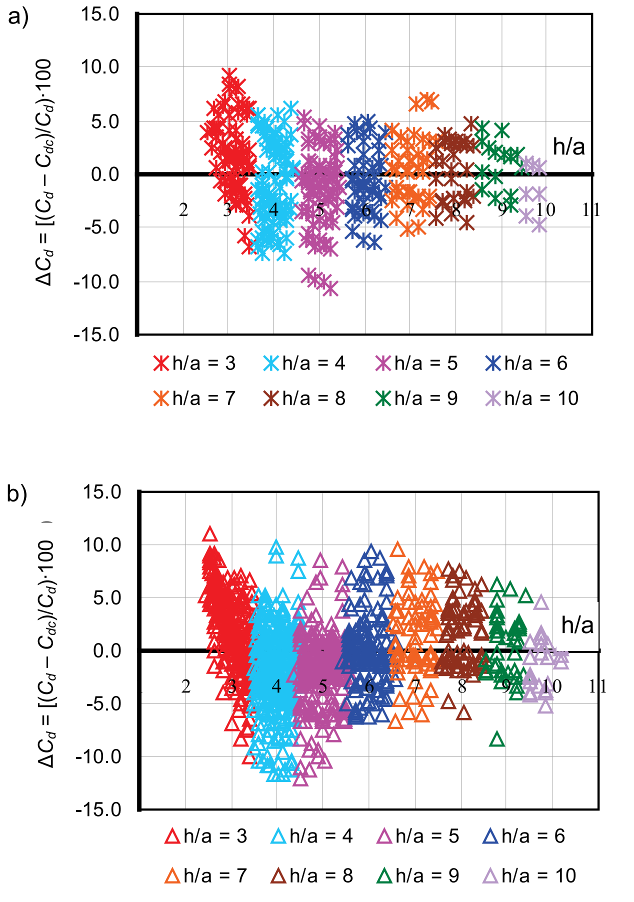

Fig. 8. The percentage deviations of values of discharge coefficient (ΔC_d) obtained from the measurements and the calculated discharge coefficient (C_{dc}) using: a) the Equation (6a) in the variant V1, b) the Equation (6b) in the variant V2; source: own study

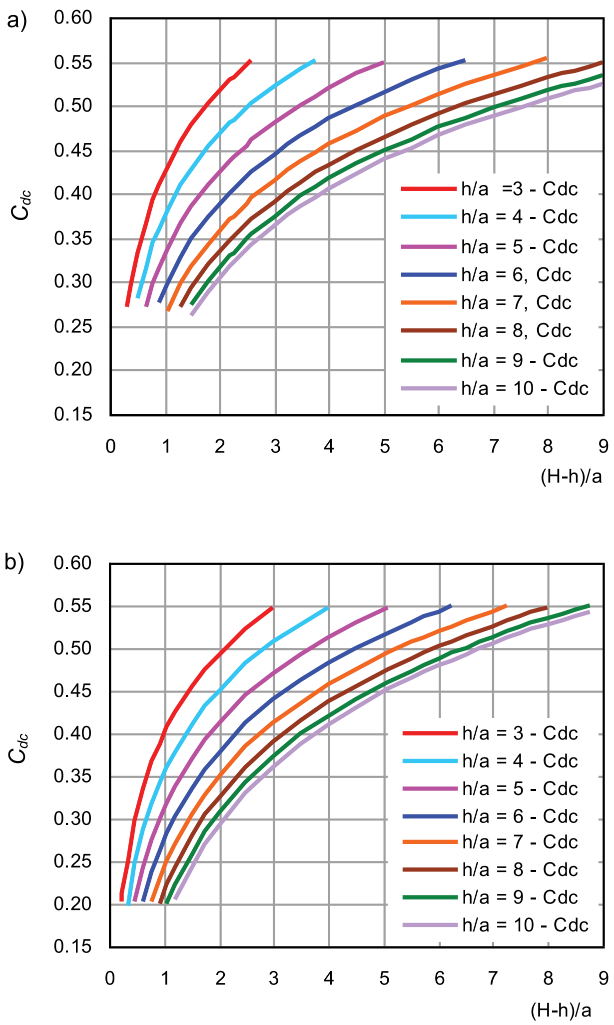

Fig. 9. Discharge coefficients as a function of the ratio of difference depths to the sluice gate opening $(H - h)/a$ and the ratio of the water depth downstream to gate opening h/a obtained from the measurements of discharge coefficient (C_d) and calculated discharge coefficient (C_{dc}): a) from the Equation (6a) for the variant V1, b) from the Equation (6b) for the variant V2; source: own study

INFLUENCE OF NARROWING THE RECTANGULAR SECTION OF THE SLUICE GATE

Narrowing in the cross-section of the gate does not affect the depth h of the lower water below the sluice gate, as it depends on the capacity of the irrigation channel. As can be seen from the Equation (1), with a constant water flow rate, narrowing, i.e. reducing the width b in the sluice gate cross-section, will increase the upstream water depth H and will affect the value of the discharge coefficient C_d. Figure 10 shows the ratios of the flow coefficients C_{dV1} determined in the variant 1 with narrowing to the values of C_{dV2} determined in the variant 2 without narrowing as a function of the upstream and downstream depth difference and opening of the sluice gate.

In order to show the influence of the upper and lower water depth on the ratios of the discharge coefficients for the submerged outflow from the sluice gate, the ratios $(H - h)/a$ for successive values of h/a = 3, 4, ..., 8 were converted to H/h (Fig. 11).

As can be seen from Figures 9 and 10, narrowing causes an increase in the discharge coefficients at downstream water depths from h/a = 3 to h/a = 5. With h/a equal to 6, 7 and 8, narrowing reduces the value of the discharge coefficients in relation to the value without narrowing. Narrowing in the sluice gate cross-section has the greatest impact on the values of the discharge

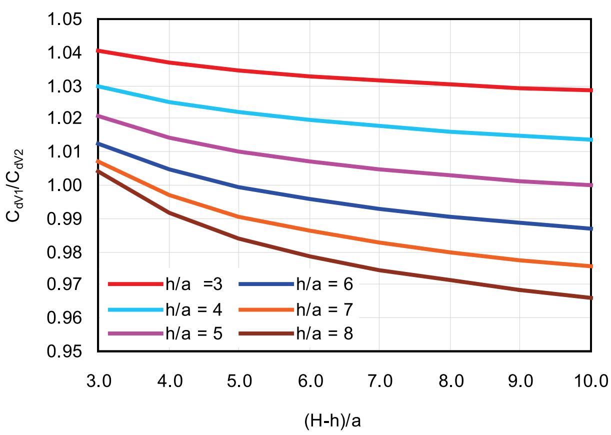

Fig. 10. Ratios of the discharge coefficients for variant 1 (C_{dV1}) calculated on the basis of the measurements in variant 1 to the value of the discharge coefficients for variant 2 (C_{dV2}) as a function of the bleed and opening of the sluice gate; source: own study

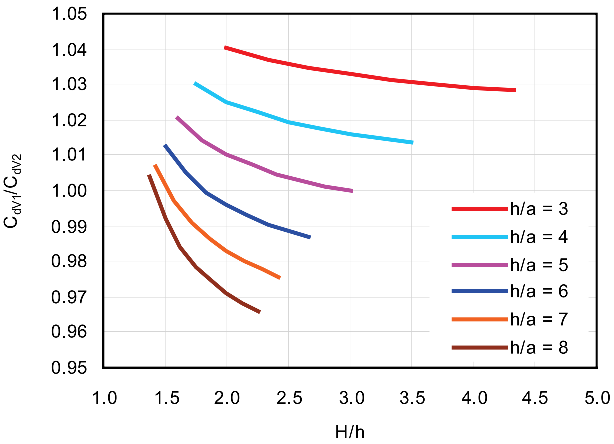

Fig. 11. Ratios of the values of the discharge coefficients (C_d) calculated on the basis of the measurements in variant 1 (C_{dV2}) to the value of the discharge coefficients for variant 2 (C_{dV2}) as a function of the ratio of the upstream water depth to the downstream water depth (H/h); source: own study

coefficients at shallow downstream water depths in relation to the gate opening. With h/a = 3, the discharge coefficients determined for a gate with narrowing are 4% higher at the water depth ratio H/h = 2.0 than the coefficients for a gate valve without throttling (Fig. 11). The effect of narrowing on the flow rates decreases with increasing upstream water depth of the sluice gate and is equal to 4% at H/h = 6.

The increase of the downstream water depth in relation to the opening of the gate causes smaller and smaller differences in the values of the discharge coefficients for the variant with and without narrowing. When h/a > 5, narrowing causes a reduction in the discharge coefficients compared to the value without narrowing. The differences in the discharge coefficients are the greater the higher the depth ratios H/h, i.e. the higher the water outflow velocities in the cross-section of the gate opening.

CONCLUSIONS

1. Downstream water depths measured with a pin gauge in the axis of the trapezoidal channel and the obtained with piezometer are consistent only at a certain distance from the gate in which there is a hydrostatic pressure distribution. Only these depth values should be used to determine the volumetric flow rate of outflow from the sluice gate.
2. The values of the discharge coefficients determined in the channels with rectangular cross-sections are not useful for the discharge coefficients of sluice gates check structures installed in trapezoidal channels.
3. The regressive dependence for discharge coefficients of sluice gates with submerged outflow installed in the trapezoidal channels was obtained by linking the determined values of the discharge coefficients with the ratio of the upstream and downstream water depth difference to the height of the gate opening and downstream water depth to the height of the gate opening $C_{dc} = \left(\frac{H-h}{a}, \frac{h}{a}\right)$.
4. The water flow rate under the gate can be calculated using the dependence (6a) and (6b) or from the curves given in Figure 9, using the measured upstream water depths (H), downstream water depth (h) and the gate opening height (a). The differences in volumetric flow rates calculated from dependences (6a) and (6b) and measured values do not exceed 10%, which confirms their practical suitability for calculating the discharge through a sluice gate mounted in a trapezoidal channel.
5. Narrowing in the cross-section of sluice gate causes an increase in the flow rates compared to the value without narrowing with ratios h/a varying from 3 to 5. With h/a values greater than 6, the value of the discharge coefficients decreases in relation to the value without narrowing. The differences in the values of the compared discharge coefficients increase with the H/h ratio.

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