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ESTIMATION OF DISCHARGE IN A LABORATORY CHANNEL USING VIDEO PROCESSING

Abstract:

This paper presents the applicability of video-based image processing techniques for discharge estimation in a laboratory channel. Surface velocities were determined using the optical flow (OF) method, and the corresponding discharge was estimated based on these measurements. The obtained results were compared with values measured using a discharge measurement device, as well as with discharge values derived from water depth measurements at the weir. The comparison of these methods indicates that the video-based approach provides reliable results for higher discharge rates, whereas larger deviations are observed at low discharges. The results highlight the potential applicability of this method under constrained laboratory conditions.

Keywords: discharge, surface velocities, videometry, optical flow, weir, laboratory channel

ПРОЦЈЕНА ПРОТОКА У ЛАБОРАТОРИЈСКОМ КАНАЛУ ТЕХНИКОМ ОБРАДЕ ВИДЕО СНИМКА

Сажетак:

У раду је приказана могућност примјене технике обраде видео снимка за процјену протока у лабораторијском каналу. Површинске брзине су одређене методом оптичког тока (OF), а на основу њих је извршена процјена протока. Добијени резултати су упоређени са вриједностима одређеним помоћу уређаја за мјерење протока, као и са вриједностима протока добијених на основу мјерења дубине на прагу. Поређењем ових метода утврђено је да метода обраде видео снимка даје поуздане резултате за веће вриједности протока, док су код малих протока одступања израженија. Резултати указују на могућност примјене ове методе у ограниченим лабораторијским условима.

Кључне ријечи: проток, површинске брзине, видеометрија, оптички ток, праг, лабораторијски канал.

1. INTRODUCTION

The measurement and estimation of discharge represent one of the fundamental tasks of hydraulic engineering, both under laboratory and field conditions. Traditional discharge measurement methods, which rely on the use of hydraulic structures or reliable measuring devices, are still regarded as accurate; however, they often require complex installation procedures and controlled operating conditions. A particular challenge is associated with the measurement of small discharges, where water viscosity becomes dominant and even relatively small deviations in water level or velocity readings can lead to significant errors in discharge calculations [1].

With the development of high-resolution digital cameras and advanced computer vision techniques, non-contact methods for estimating velocities and discharge from video recordings have gained increasing attention in recent decades. These approaches, commonly referred to as videometry (or videography), enable the retrieval of the spatial distribution of surface velocities without physical contact or interference with the flow, making them especially suitable for investigations under conditions of limited accessibility or increased sensitivity of the measurement site [1], [2].

One of the widely used techniques within videometry is the optical flow method, which allows for the estimation of velocity fields by analyzing changes in pixel intensity between successive frames of a video sequence. An efficient estimation of displacement vectors for each pixel is achieved through an approach based on the polynomial approximation of the image intensity function [3]. Owing to these characteristics, the optical flow method has found broad application in open-channel flow research.

More recently, specialized software tools have been developed that integrate optical flow techniques with additional processing steps, such as video stabilization and data filtering. One such tool is SSIM-Flow, which is primarily intended for the estimation of surface velocities and discharge from video recordings [4]. Although the tool was originally developed for mobile platforms such as unmanned aerial vehicles, its application is also feasible under laboratory conditions where video data are acquired using a fixed camera setup.

The objective of this study is to investigate the applicability of the optical flow method for discharge estimation in a laboratory channel at the Hydraulic Engineering Laboratory of the Faculty of Architecture, Civil Engineering, and Geodesy, and to compare the obtained results with indirect methods such as the Froude-based method derived from the minimum energy condition at a triangular-crested weir. The research focuses on video-based discharge estimation, with particular emphasis on the measurement of small discharges.

2. MATERIALS AND METHODS

2.1. DISCHARGE ESTIMATION TECHNIQUES AND DESCRIPTION OF THE LABORATORY SETUP

Video acquisition and measurements were conducted in a laboratory channel, and the laboratory setup is schematically illustrated in Figure 1.

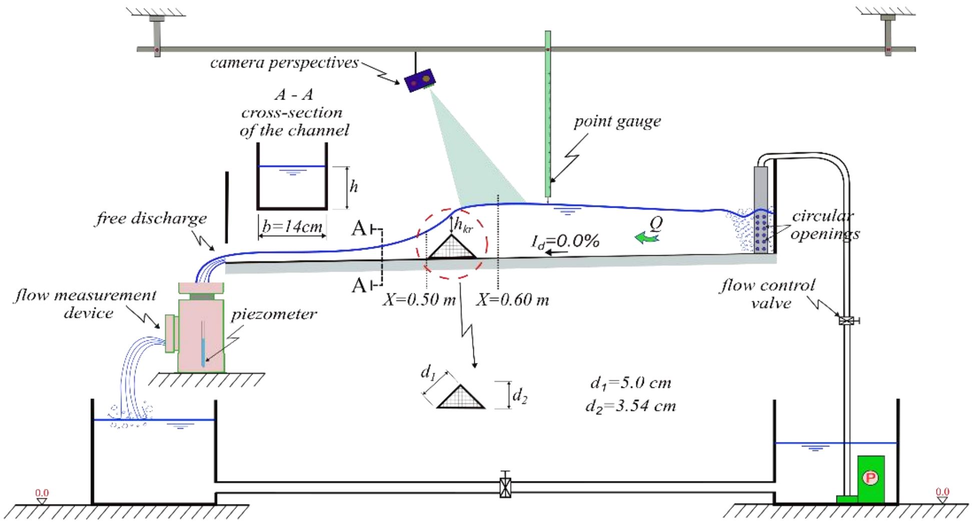

Figure 1. Schematic representation of the laboratory setup (drawing by author).

The system shown in the figure operates as follows: water is pumped from the right cylindrical reservoir with a diameter of 0.50 m by means of a submersible pump and conveyed to the channel. A ball valve installed on the discharge pipeline allows the regulation of the discharge through the system.

At the outlet of the pipeline into the channel, a so-called flow straightener is installed, consisting of a vertically oriented pipe with a diameter of 75 mm, perforated along the pipe wall with 10 mm diameter holes that allow the passage of water. This component is required to condition and redistribute the approach flow upstream of the installed weir, ensuring stable hydraulic conditions before overtopping of the crest.

The channel is made of glass, with a length of L = 1.30 m and a rectangular cross-section of width b = 14 cm. Within the channel, at a station X = 0.5 m measured from the downstream end (left), a weir with a height of 3.54 cm is installed. The position of the weir is shown in the figure, where the aforementioned station refers to the left edge of the weir. Its cross-section has the shape of an isosceles right triangle with leg lengths of 5.0 cm and is fabricated from hardwood (oak).

It should be noted that the longitudinal slope of the channel is I_d = 0.0%, and that an opening at the downstream end allows for free outflow. Water from the channel flows into a discharge measurement device [5], from which it is subsequently released into a left reservoir of the same characteristics as the right one. The two reservoirs are connected by a pipeline with a length of 3.0 m and a diameter of 75 mm, at the midpoint of which a fully open gate valve is installed. This configuration enables a recirculating (closed-loop) flow system.

The reference discharge value was taken as the value obtained from the discharge measurement device, as this device had been previously tested under laboratory conditions and verified in field applications. This is reported in the study by Praštalo et al. [5]. The following figure presents the construction of the device along with its geometric characteristics.

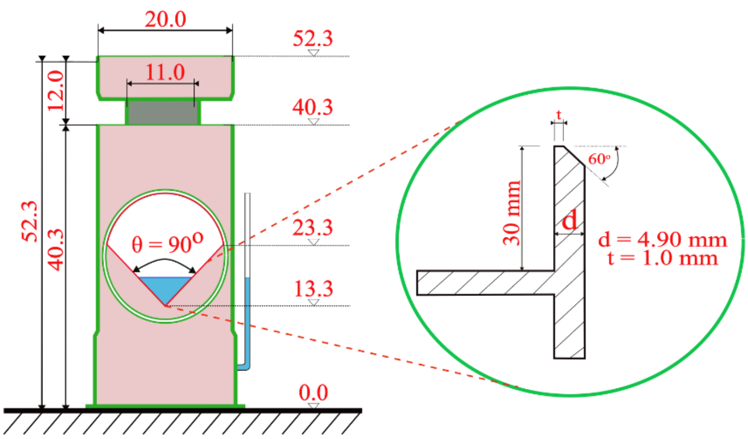

Figure 2. Discharge measurement device with geometric characteristics [5].

The discharge measurement device is constructed from T-shaped PVC sewer pipe elements with a nominal diameter of DN 200/200 mm. The lower side is closed, while the remaining sides are open. On the lateral side, a cap is installed in which a precisely machined 90° "V notch" (Thompson) weir is formed. Inside the device, a vertical sewer pipe with a nominal diameter of DN 110/160 mm is installed, perforated around its circumference with circular holes of 10 mm diameter. The function of this pipe is to act as a flow straightener, allowing the water to rise from the bottom toward the weir and fill the lower part of the device until the water level reaches the crest elevation. A piezometer is mounted along the side of the pipe, where the water level is measured, corresponding to the head at the weir crest. The geometric characteristics of the device and the detailed shape of the weir are shown in Figure 2 [5].
The discharge over the "V notch" weir can be expressed as [6]:

$$Q = \frac{8}{15} C_d \sqrt{2g} h_p^{5/2} \tag{1}$$

where Q (m^3/s) is the discharge, C_d (-) is the discharge coefficient, g (m/s^2) is the gravitational acceleration, and h_p (m) is the head over the weir, calculated as the difference between the water level measured in the piezometer and the weir crest elevation of 13.3 cm.
After calibration of the weir according to Model 3 proposed by Praštalo et al., the discharge coefficient can be expressed as [5]:

$$C_d = 0.6703 + 0.0161(h_p/P) \tag{2}$$

where P (mm) is the weir height, equal to 30 mm, as shown in Figure 2.
A fixed camera is mounted above the channel to acquire the video recordings. In this study, a Venture 5K Duo camera was used. This is an action sports camera capable of recording high-resolution video up to 5K (ultra-high resolution) as well as high-megapixel still images. The video recordings are used to identify surface velocities, from which the discharge is subsequently estimated. The following figure shows the appearance of the camera and an example frame captured during the recording of surface velocities in the laboratory channel.

Figure 3. Venture 5K Duo camera (left)[7] and an example recorded frame (right) (photography by author).

The laboratory setup also includes a point gauge (shown in Figure 1), which is used for point-wise measurement of the water depth at the weir crest. The channel conditions enabled free (unsubmerged) flow over the weir, such that critical depth h_{cr} is established at the crest, and the minimum specific energy condition is satisfied ($e_{min} = h_{cr} + v_{cr}^2/2g$). The minimum specific energy occurs when the Froude number equals unity [6]:

$$Fr = \frac{Q^2 B}{g A^3} = 1 \tag{3}$$

where Fr (-) is the Froude number, B (m) is the water surface width, which in this case is equal to the channel width b = 14 cm, and A (m^2) is the cross-sectional flow area. In this study, the weir has the shape of an isosceles right triangle, where the sharp edge defines the location of the critical depth, facilitating measurement, as illustrated in the Figure 4.

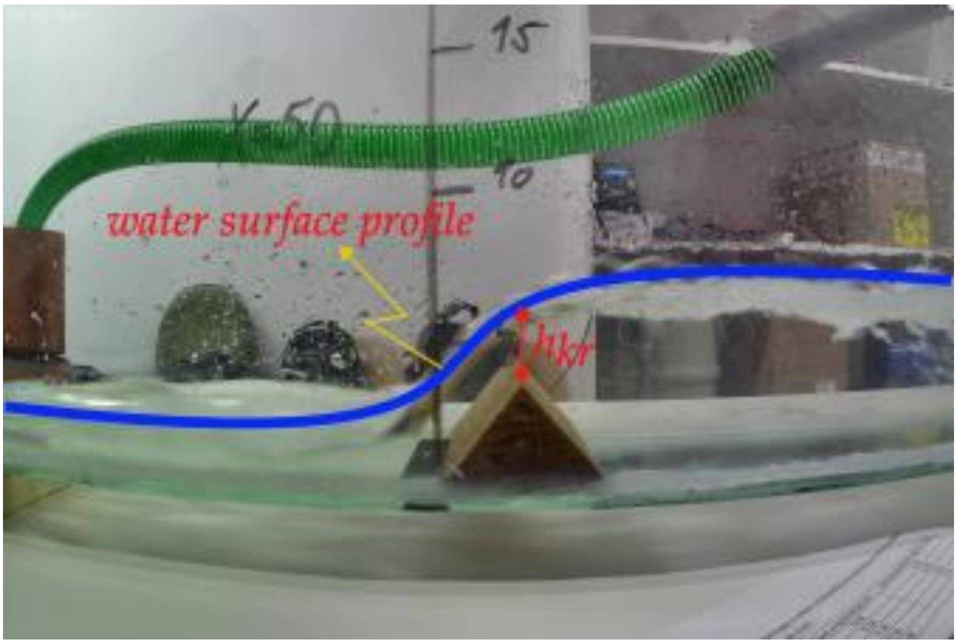

Figure 4. Water surface profile at the weir crest in the laboratory channel (photography by author).

The cross-sectional flow area at the weir can be expressed as $A = b \cdot h_{cr}$. Substituting this expression into Eq. (3), the discharge can be written as:

$$Q = \sqrt{g \cdot h_{cr}^3 \cdot B^2} \quad (4)$$

The discharge values obtained using this method were used for comparison with the discharge values derived from video processing, relative to the reference discharge values obtained from the discharge measurement device. The relative error was adopted as a measure of deviation from the reference value and is defined as:

$$\varepsilon = \frac{|Q_{calc} - Q_m|}{Q_m} \cdot 100\% \quad (5)$$

where ε (%) is the relative error, Q_{calc} is the discharge estimated by one of the two applied methods, and Q_m is the discharge measured by the discharge measurement device.

For further comparison, the mean absolute percentage error (*MAPE*) was also used, representing the average percentage difference between the reference discharge values and those obtained by the applied methods. It is calculated as:

$$MAPE = \frac{1}{n} \cdot \sum_{i=1}^{n} \left| \frac{Q_m - Q_{calc}}{Q_m} \right| \cdot 100\% \quad (6)$$

where $MAPE$ (%) is the mean absolute percentage error, and n is the total number of samples, which in this study was equal to 5.

2.2. VIDEO PROCESSING TECHNIQUE

Surface velocities can be identified from video recordings using various image processing techniques, which are then used to estimate discharge. Some of the most commonly applied methods include [8]:

- Particle Image Velocimetry – PIV,
- Particle Tracking Velocimetry – PTV,
- Kanade-Lucas-Tomasi – KTL,
- Optical Flow – OF,
- Surface Structure Image Velocimetry – SSIV,
- Space-Time Image Velocimetry – STIV.

In this study, the optical flow (OF) method was employed. It is based on the analysis of pixel intensity gradient fields between successive images (frames) of a video sequence. The method was originally developed by Gunnar Farnebäck [3].

The basic principle assumes that the motion of structures between two successive time instants (i.e., two frames) can be estimated by analyzing changes in pixel intensities. Each pixel is approximated by a second-order polynomial, which allows the local image structure to be described. The motion between two consecutive frames is modeled as a translation of this polynomial approximation. By comparing the polynomial coefficients between frames, an analytical expression for the displacement vector can be derived. In this way, information on the velocity of each individual pixel is obtained, and by repeating the procedure over all successive frames, the spatiotemporal motion of objects in the video sequence can be characterized [3].

In contrast to feature-based methods that track only characteristic points, this approach enables the estimation of a dense velocity field, as a motion vector is obtained for each pixel in the image. Owing to this property, the method is widely adopted in videometric applications for surface velocity estimation.

For video processing, a ready-made library package for optical flow available in the Python programming language was used. This package provides a range of pre-processing and data processing steps for video recordings, as well as discharge estimation capabilities. By tracking the motion of characteristic points between successive frames, local surface velocities are estimated and subsequently spatially averaged across the channel width. This approach enables the processing of video sequences in which pixel displacement velocities are relatively high. Based on the obtained mean surface velocity and the known cross-sectional geometry of the channel, the discharge was calculated.

3. RESULTS AND DISCUSSION

As previously stated, the discharge was estimated based on measurements of the critical depth at the weir profile, using the minimum specific energy condition at the crest. In parallel, surface velocities were identified using video processing techniques in order to derive the corresponding discharge. The results obtained by these methods are presented in the following table relative to the measured discharge values.

Table 1. Discharge values

Upstream depth (X=0.60m) (cm)	Measured (l/s)	Froude based method (l/s)	Optical flow based discharge (l/s)
6.40	1.94	2.040	1.925
5.40	1.60	1.721	1.595
4.90	1.20	0.800	1.354
4.80	0.80	0.312	0.621
4.70	0.40	0.255	0.567

Using the critical depth measurements and the Froude-based method, reliable results – defined here as relative errors below 10% with respect to the reference discharge measured by the calibrated discharge measurement device – were obtained for only two discharge values (1.60 and 1.94 L/s). For the remaining cases, this method underestimates the discharge relative to the reference measurements. Similarly, the optical-flow-based method provides good agreement with the reference discharge values for the higher discharges (1.60 and 1.94 L/s). For a discharge of 0.80 L/s, the optical method underestimates the discharge, while for 0.40 L/s it overestimates it. A comparison of the estimated and measured discharge values is shown in the following figure.

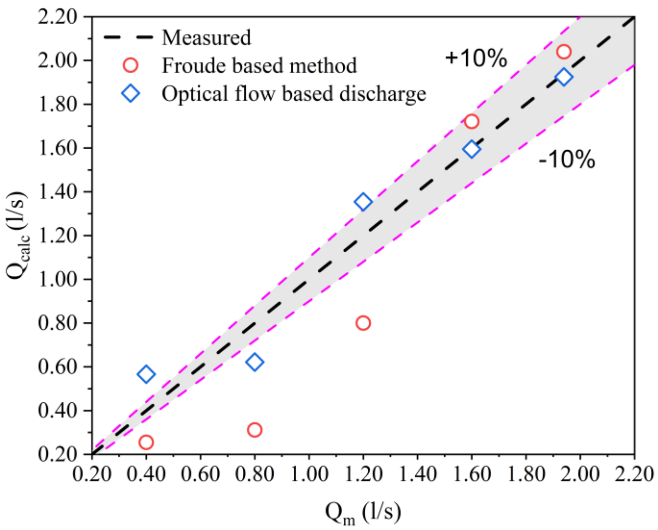

Figure 5. Comparison of discharge estimates (diagram by author).

As can be observed in Figure 5, the critical-depth-based (Froude) method exhibits larger deviations from the measured values for lower discharges (0.40, 0.80, and 1.20 L/s). This behavior is attributed to the difficulty of accurately reading the critical depth using the point gauge, which introduces a larger measurement error into the discharge estimation. For the remaining discharge values, the relative error is less than 10%.

With respect to the video processing technique, the results are somewhat better; however, noticeable deviations are still observed at lower discharge values, where the relative error exceeds 10%. Considering the fact that very low discharges (below 1.0 L/s) are inherently difficult to measure, larger measurement errors are to be expected.

When comparing the mean absolute percentage error (MAPE), the Froude-based method yields a value of 28.67%, whereas the optical method results in a lower MAPE of 15.58% over the considered range of discharge values.

In terms of individual values, the smallest relative errors occur for discharges of 1.60 and 1.94 L/s. For the optical method, the relative error is below 1.0% for both values, while for the Froude-based method the corresponding errors are 7.50% and 5.14%, respectively. The largest relative error for the Froude-based method is obtained at a discharge of 0.80 L/s, amounting to −61.06%, whereas for the optical method the largest relative error occurs at 0.40 L/s and reaches 41.63%. The box plot of the relative error for the applied methods is shown in the following figure.

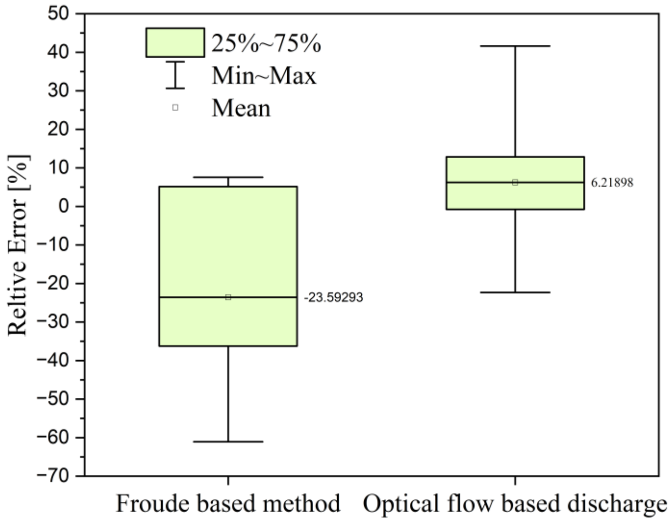

Figure 6. Box – plot of relative error (diagram by author).

For improved visualization and interpretation of the results, a Bland–Altman analysis was also performed [9]. Both methods exhibit a tendency to overestimate the discharge. However, the optical flow method demonstrates smaller dispersion and better consistency of the results, while deviations are more pronounced at lower discharge values. The Froude-based method shows larger deviations, particularly at lower mean values, indicating greater errors in the measurement of water depth at the weir profile. For both applied methods, most data points lie within the boundary for a standard 95% confidence interval (±1.96 Standard Deviation), and the points are more concentrated around the zero-difference line than around the mean difference.

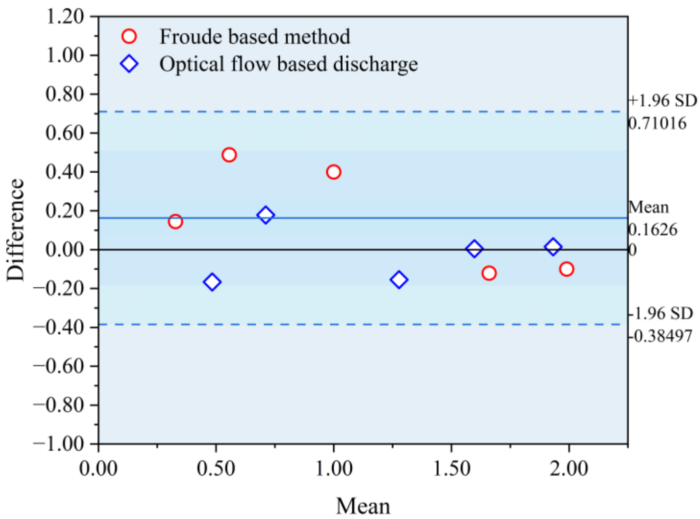

Figure 7. Bland – Altman analysis of the applied methods (diagram by author).

4. CONCLUSION

This study demonstrates the feasibility of estimating discharge in a laboratory channel using a video processing technique, with the results compared to an indirect method based on critical depth measurements at a weir. The estimation of low discharges under laboratory conditions is a demanding task that requires high-quality and precise measurement equipment. Traditionally, discharge measurement using hydraulic structures has been the standard practice in hydraulic engineering. With the development of accurate and high-speed cameras, this task can also be performed using video-based techniques.

The results of the present investigation indicate that video processing techniques can be reliably applied for discharges greater than 1.0 L/s, for which consistent and accurate estimates are obtained. For lower discharge values (below 1.0 L/s), the relative error in discharge estimation increases (exceeding 10%), making this technique less reliable in that range.

The optical flow method employed in this study demonstrates better stability and lower systematic error compared to the Froude-based method, while both methods remain within the boundary for a standard 95% confidence interval. Future research should focus on improving optical-flow-based video processing techniques in order to enhance the reliability of discharge estimation for low-flow conditions.

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