Study of velocity field at model sideweir using visualization method

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Technical note

Study of velocity field at model sideweir using visualization method

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ABSTRACT

A visualization method was employed for accurate non-intrusive measurement of velocity fields at a physical model of a sharp-crested rectangular sideweir under subcritical flow. The experimental observation of velocity vectors at various horizontal planes over the entire width of the main channel confirms that the flow conditions at sideweir are non-uniform. The coefficients of non-uniform velocity distribution were in the range from 1 to 1.1. The present study focuses on the relation between the longitudinal components of the overflow velocities and the corresponding cross-sectional average velocities in the main channel, detailed as a function of flow depth and of location along the sideweir crest. For different sideweir geometries, these coefficients varied between 1 and 1.2.

Keywords: Laboratory experiment, model study, open channel flow, sideweir, velocity field, visualization

1 Introduction

Sideweirs are hydraulic structures for diverting discharge from a main channel to a lateral. They are widely used to control discharge in irrigation, sewer, and flood management systems.

The performance of sideweirs was investigated from the pioneering work of De Marchi (1934), seminal work of Hager (1982, 1983, 2010), to recent work of Emiroglu et al. (2011). Most concentrated on the total lateral outflow $Q_s$, the free surface profile, and the discharge coefficient $C_d$. In contrast, this work focuses on the experimental determination of the velocity field of a model sideweir using a non-intrusive visualization method. The velocity-related terms are included in the fundamental one-dimensional equation for spatially-varied flow. Its energy-approach-based form includes the kinetic energy coefficient $\alpha$, while the momentum-approach-based equation includes the overflow velocity component parallel to main channel axis $U$, the average channel flow velocity $V$, and the momentum coefficient $\beta$. The measured velocity fields indicate either $U = V$, as assumed in the constant energy approach, or $U > V$, as implied by the momentum approach. Using non-intrusive visualization causes accurate flow observations result, whereas intrusive instrumentation causes significant flow perturbations.

Recent works based on the constant energy approach are by Singh et al. (1994), Swamee et al. (1994), Borghi et al. (1999), or Rosier et al. (2010). The effect of specific energy variation was considered by Yüksel (2004) and Venutelli (2008). Representative works based on the momentum approach are by El-Khashab and Smith (1976), Hager and Volkart (1986), Lee and Holley (2002), or May et al. (2003).
2 Methodology

The velocity field of sidewayr flow can be determined using either pathlines or streaklines (Kline 1969). The non-intrusive computer-aided visualization method of Bajcar et al. (2009) was employed. This method determines the vector velocity field from a scalar field of pollutant concentrations using the sequence of grayscale images of the observed flow. This approach is based directly on the physical advection–diffusion equation representing the basic connection between pollutant concentration and the flow kinematics as

\[
\frac{\partial N}{\partial t} + \frac{\partial (NV_i)}{\partial x_i} = DV^2 N
\]  

(1)

By knowing concentration \( N \), its derivatives, and the molecular diffusivity \( D \) of the pollutant, the only unknown is velocity, i.e. its components \( v_i \) in the directions \( x_i \). The pollutant is introduced to the fluid, then illuminated and digitally recorded on a high-speed film. The grayscale values of these images correspond to the relation \( A \propto N \), where \( A \) is an average grayscale value in the selected window of pixels on a grayscale image. Both temporal and spatial derivatives of concentration in Eq. (1) are approximated by knowing the duration between two successive images and the dimensions of grayscale images. The approximated spatial derivatives are then numerically determined.

The method differs from other visualization methods based on the correlation of successive flow images. Furthermore, the method does not require timelines, as employed by Dargahi (1997), and works well with pollutants such as dye, bubbles, or particles. Herein, the electrolysis-generated hydrogen bubbles were employed as the most suitable pollutant for a small testing facility.

Okamoto et al. (1971) specified the uncertainties of the hydrogen bubble visualization as (1) horizontal streamline shift by buoyancy, (2) entry length for bubble acceleration, (3) wake flow behind wire, (4) centripetal force in curved flow, and (5) decaying time by absorption. The optimum bubble diameter, which is comparable to the wire diameter, is 0.06–0.15 mm (Okamoto et al. 1971, Tropea et al. 2007). Following the latter, a wire of 0.5 mm diameter was used. Also, 1 kg of common salt was added per 3 m³ of water to produce bubbles of less than 100 V (Dargahi 1997). To address the above issues, a preliminary test was conducted to experimentally optimize the wire position, to adjust the image acquisition equipment, and to calibrate the settings for numerical calculation. Calibration tests with plastic and cork particles were performed as well. The resulting velocities from the calibrated visualization method \( V_c \) agreed well with these observed with floats \( V_f \), i.e. \( V_c/V_f = 1(\pm3\%) \).

3 Experimental setup

Six types of Plexiglas sidewayrs involving various crest lengths \( L \) and crest heights \( p \) were tested in a glass-walled horizontal flume 7.5 m long, 0.2 m wide, and 0.5 m deep (Fig. 1). The flow was always subcritical. The inflow \( Q_s \) and outflow \( Q_t \) discharges were measured with V-notch weirs, while \( Q_t = Q_1 - Q_2 \). Free surface elevations were measured using a point gauge of ±0.1 mm reading accuracy and photos of laser-induced vertical sections of the flow. The flow depth \( h_2 \) at the downstream sidewayr end was adjusted for each \( Q_1 \) to provide modular discharge \( Q_t \) and sufficient overflow depth \( h - p \geq 19 \) mm (Emiroglu et al. 2011) to avoid surface tension effects. The main hydraulic conditions are given in Table 1. The study was based on a relatively narrow channel, yet the dimensionless parameters were mostly within the ranges of previous investigations (Table 2).

The velocity fields were recorded at five horizontal planes, located by \( z_w \) above the sidewayr bed. Four distances \( z_w \) were
Table 1  Main test parameters, with $h - p$ measured at $L/2$

<table>
<thead>
<tr>
<th>Weir</th>
<th>$L = 25, p = 12$ [cm]</th>
<th>$L = 20, p = 12$ [cm]</th>
<th>$L = 20, p = 10$ [cm]</th>
<th>$L = 15, p = 10$ [cm]</th>
<th>$L = 15, p = 7.5$ [cm]</th>
<th>$L = 10, p = 7.5$ [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>$Q_1$ (l/s)</td>
<td>$Q_2$ (l/s)</td>
<td>$Q_1/Q_2$ ($)</td>
<td>$Q_1$ (l/s)</td>
<td>$B/L$ ($)</td>
<td>$F_1$ ($)</td>
</tr>
<tr>
<td>------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>----------------------</td>
<td>----------------------</td>
</tr>
<tr>
<td></td>
<td>6.34</td>
<td>0.08</td>
<td>0.08</td>
<td>6.45</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>6.94</td>
<td>0.08</td>
<td>0.08</td>
<td>6.62</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>7.83</td>
<td>0.08</td>
<td>0.08</td>
<td>7.59</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>5.45</td>
<td>0.08</td>
<td>0.08</td>
<td>5.29</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>6.62</td>
<td>0.08</td>
<td>0.08</td>
<td>6.01</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>7.59</td>
<td>0.08</td>
<td>0.08</td>
<td>6.62</td>
<td>1.2</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 2  Ranges of measured parameters from previous and present studies

<table>
<thead>
<tr>
<th>Authors</th>
<th>$B$ (cm)</th>
<th>$L$ (cm)</th>
<th>$p$ (cm)</th>
<th>$S_a$ (%)</th>
<th>$Q_1$ (l/s)</th>
<th>$B/L$ ($)</th>
<th>$F_1$ ($)</th>
<th>$Q_1/Q_1$ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>El-Khashab and Smith (1976)</td>
<td>46</td>
<td>120,230</td>
<td>10–25</td>
<td>Varied</td>
<td>≤220</td>
<td>0.2–0.38</td>
<td>≤1.2</td>
<td>0.3–0.8</td>
</tr>
<tr>
<td>Balmforth and Sarginson (1983)</td>
<td>100</td>
<td>46–76</td>
<td>4–12</td>
<td>–</td>
<td>–</td>
<td>0.46–0.76</td>
<td>Varied</td>
<td>–</td>
</tr>
<tr>
<td>Hager and Volkart (1986)</td>
<td>30</td>
<td>100</td>
<td>0–20</td>
<td>–4 to 5</td>
<td>0.45</td>
<td>0.3</td>
<td>0.3–2</td>
<td>–</td>
</tr>
<tr>
<td>Singh et al. (1994)</td>
<td>25</td>
<td>10–20</td>
<td>6–12</td>
<td>–</td>
<td>10–14</td>
<td>1.25–2.5</td>
<td>0.2–0.4</td>
<td>–</td>
</tr>
<tr>
<td>Swamee et al. (1994)</td>
<td>50</td>
<td>20–50</td>
<td>0–60</td>
<td>0</td>
<td>20–100</td>
<td>1–2.5</td>
<td>0.1–0.93</td>
<td>–</td>
</tr>
<tr>
<td>Borghei et al. (1999)</td>
<td>30</td>
<td>20–70</td>
<td>1,10,19</td>
<td>0.5 to 1</td>
<td>35–100</td>
<td>0.43–1.5</td>
<td>0.1–0.9</td>
<td>–</td>
</tr>
<tr>
<td>Pinheiro and Silva (1999)</td>
<td>50</td>
<td>150,200</td>
<td>20</td>
<td>–</td>
<td>25–150</td>
<td>0.25–0.33</td>
<td>&lt;1</td>
<td>0.25–0.75</td>
</tr>
<tr>
<td>May et al. (2003)</td>
<td>21–60</td>
<td>20–100</td>
<td>5–25</td>
<td>0</td>
<td>0.21–3</td>
<td>&lt;1</td>
<td>0.08–1</td>
<td>–</td>
</tr>
<tr>
<td>Present study</td>
<td>14</td>
<td>10–25</td>
<td>7.5–12</td>
<td>0</td>
<td>4–4.7</td>
<td>0.56–1.4</td>
<td>0.28–0.34</td>
<td>0.20–0.27</td>
</tr>
</tbody>
</table>

4 Results

4.1 Velocity fields

For all sideweir geometries and combinations of the inflow $Q_1$ and flow depth $h_2$, the measured velocity fields were non-uniform. Figure 2 shows a typical velocity field for $z_w = p$. As expected, the measured longitudinal velocity components decrease with distance from water surface and also in the direction $x$, while the outflow angle increases with $x$. At the downstream sideweir end, weak standing waves were formed selected in relation to $p$, i.e. $z_w/p = 0, 1/3, 2/3$, and 1, respectively, while the fifth plane was located 5 mm below the free surface. The illumination was placed at $z_w$ on both channel sides to illuminate a 5 mm high horizontal layer, reaching over the entire sideweir width. The distance between the wire and the upstream sideweir end was constant. To maintain recording quality, the voltage of the adjustable DC source was increased for higher $z_w$. The camera was placed vertically above the channel. For each test, some 1500 images were recorded at 300 frames/s and then converted into grayscale images. Sets of 500 images were employed to determine the velocity vectors in each pixel along a selected section. Three sets were averaged to obtain the plane velocity components $V_x$, $V_y$, and $U_x, U_y$. The standard deviation of the velocity components was on average 0.6. Various parameters of the numerical calculation can be adjusted; the pixel size proved to be an important factor, and was adjusted for each $z_w$.

4.2 Velocity distribution coefficients

In general, the coefficients $\alpha$ and $\beta$ increased along the sideweir from 1.02 to 1.08 and from 1.01 to 1.03, respectively, in agreement with $\alpha = [1 + (q/Qs)^2]^{1/3}$ of Hager (1982), with $q$ being the unit overflow discharge. Also, values $\alpha$ at given $x/L$ increased from type (a) to type (c) test runs. At cross sections 0.5$L$ upstream and downstream of the sideweir, respectively, the coefficients $\alpha$ were similar to those at $x/L = 0$ and 1, respectively.

The coefficients $\beta$ were close to unity in all tests. The data confirm that “approximately, $\beta$ can be replaced by unity” (Hager 1983). However, $\beta$ was significantly below the constant 1.23, as proposed by May et al. (2003), who suggested $\beta = 0.725 + 0.275(U/V)$. 

Figure 2  Typical plane velocity field above the crest. At the end of the sideweir, velocities near the main channel bed decreased.
4.3 Relation $U/V$

Values of $U/V = f(h/p)$ were measured for $h/p$ values ranging from 1.15 to 1.4, resulting in $U/V \approx 1–1.2$ (Fig. 3a). For a given geometry, the $U/V$ ratio increases with $h/p$. Figure 3(b) also shows that $U/V$ increases with the distance from the upstream end of the sideweir. It is evident that $U/V > 1.1$ at $x/L = 1$ for all sideweir geometries tested.

5 Conclusions

A visualization method was employed for accurate non-intrusive measurement of the velocity fields at sharp-crested model sideweirs in subcritical flow. The data indicate that the velocity distribution is highly non-uniform. Both the kinetic energy and momentum correction coefficients vary along the sideweir on the average from 1.02 to 1.08, and 1.01 to 1.03, respectively, in agreement with an available proposal. Furthermore, the ratio of the longitudinal overflow velocity component and the average sideweir velocity varies essentially with the ratio of flow depth to weir height. This ratio also varies along the sideweir. The present data confirm the assumption of non-uniform velocity distribution, as implied by the momentum approach. The results of this study apply for calibrating numerical models of sideweir flow.

Notation

- $F_1 = \text{approach flow Froude number} (-)$
- $L = \text{length of sideweir (m)}$
- $p = \text{height of sideweir crest (m)}$
- $Q_1 = \text{approach flow discharge (m}^3/\text{s})$
- $Q_s = \text{discharge over sideweir (m}^3/\text{s})$
- $U = \text{streamwise sideweir velocity component (m/s)}$
- $V = \text{average main channel flow velocity (m/s)}$
- $z_w = \text{observed horizontal plane (m)}$
- $\alpha = \text{kinetic energy correction coefficient} (-)$
- $\beta = \text{momentum correction coefficient} (-)$

References


