MEAN AND TURBULENT FLOW CHARACTERISTICS IN SUPERCritical NARROW OPEN CHANNEL FLOWS: EFFECT OF FROUDE NUMBER

DILA DEMIRAL
Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Hänggerbergring 26, 8093 Zurich, Switzerland
demiral@vaw.baug.ethz.ch

ABSTRACT
Sedimentation threatens the sustainability of many reservoirs worldwide. The need for active sediment handling such as sediment routing using Sediment Bypass Tunnels (SBT) or Sediment Flushing Channels (SFC) will consequently increase considerably in the future to maintain reservoir storage capacities as well as to restore sediment connectivity. However, highly sediment-laden high-speed flows can cause severe hydro-abrasion at such hydraulic structures. To shed more light on the hydro-abrasion phenomenon in high-speed flows, a systematical experimental investigation on the physical processes of (I) turbulent flow characteristics, (II) bed load particle motion, (III) hydro-abrasive wear, and (IV) their interrelations in supercritical narrow open channel flows is conducted in the framework of a PhD thesis at VAW of ETH Zurich. The present study deals with the former (I). Streamwise and vertical flow velocities were measured using 2D Laser Doppler Anemometry (LDA) at a large number of verticals across the flume width over a fixed-concrete bed in a laboratory flume representing a straight SBT section. Approach flow Froude numbers were $F_d = 2$ and 4. The results show that the log-law applies in the wall region reaching up to $z/h = 0.3$, and the mean velocity patterns undulate across the flume, indicating the presence of counter-rotating secondary currents occurring at low aspect ratios below the critical value of 4 - 5. These currents cause re-distribution of turbulence intensity and Reynolds shear stress across the flume. The present findings give an insight on where sediment transport, and hence hydro-abrasion, are concentrated and finally contribute to a better understanding of the abrasion mechanics and to the development of a mechanistic abrasion model for prediction and design purposes.

Keywords: Narrow open channel flow, Laser Doppler Anemometry (LDA), supercritical flow, mean and turbulent flow characteristics, sediment bypass tunnels.

1 INTRODUCTION
Several reservoirs are or will in the near future be significantly filled with sediment due to typical annual sedimentation rates of up to 1% (Schleiss et al. 2016). The arising problems with increasing sedimentation are: (1) loss of storage volume for energy production, flood protection, irrigation or water supply; (2) hydro-abrasion at hydraulic machinery and structures; and (3) negative environmental impacts, as the downstream sediment supply is interrupted. An effective technique to counter reservoir sedimentation is to route the sediment around a dam and/or to flush sediments using SBTs, SFCs and dam outlets (Boes et al. 2014; Auel et al. 2017a, b; Müller Hagmann 2017). SBTs are typically operated at supercritical open channel flow conditions to ensure sufficient sediment transport capacity and to avoid transition to pressurized flow. Combination of high flow velocities and high sediment transport rates cause hydro-abrasion at the tunnel inverts that puts their operational safety at risk and causes high maintenance costs. Therefore, a better understanding of the abrasion mechanics and the development of a mechanistic abrasion model mimicking the hydro-abrasive wear are of prime importance for the design and sustainable use of hydraulic structures. However, there is still a lack of knowledge on the physical processes of turbulent flow characteristics, bed load particle motion, abrasion and their interrelations in highly supercritical flows, which are the key parameters of hydro-abrasion modeling. The overarching goal of the research presented herein is to mitigate hydro-abrasive wear at hydraulic structures subjected to sediment-laden flows. The objectives of the study are to investigate the (I) mean and turbulent flow characteristics in supercritical open channel flows over fixed and abraded-fixed beds with a focus on low aspect ratios (channel width to flow depth, $b/h \leq 2$) as typically present in SBTs and SFCs, (II) sediment transport modes and particle impact energy in different flow conditions, (III) hydro-abrasion depths and patterns for different sediment supply rates using different types of bed lining materials and particles, and (IV) interrelation among flow characteristics, particle motion and hydro-abrasion. The ultimate goal is to develop a predictive mechanistic abrasion model as a tool for practitioners to optimize the design and operation of SBTs. This paper deals with the first part of the project, i.e. mean and turbulent flow characteristics (I).
Previous studies on the turbulence characteristics of open channel flows over smooth and rough beds show that the basic log-law velocity distribution applies in the wall region of the water column, i.e. for \( z/h < 0.2 \), where \( z \) is the vertical distance from the channel bed. In the outer region, an additional wake parameter represents the velocity distribution affected by the free water surface (Nikuradse 1933; Nezu and Rodi 1986; Cardoso et al. 1989; Lyn 1991; Kironoto and Graf 1994). The log-law follows a universal velocity distribution:

\[
U^* = \frac{1}{\kappa} \ln(z^*) + A, \quad z^* > 30
\]  

where \( U^* = U/u_\tau \); \( U \) = time-averaged flow velocity and \( u_\tau \) = friction velocity, \( \kappa = \text{von Kármán constant} \), \( z^* = \frac{z u_\tau}{\nu} \), \( \nu = \text{kinematic fluid viscosity} \), and \( A = \text{integral constant} \). A von Kármán constant \( \kappa = 0.41 \pm 5\% \) is widely accepted for steady, closed, and open channel flows over smooth, rough, and movable beds, and independent from Reynolds (R) and Froude numbers (F) (Coles 1956; Tominaga and Nezu 1992; Nezu and Nakagawa 1993; Bradshaw 1995; Prinos and Zeris 1995; Auel et al. 2014). For steady, fully developed open channel flow conditions, the integral constant is reported as \( A = 5.29 \) (Nezu and Rodi 1986; Auel et al. 2014). For transitionally and fully rough beds, the log-law (Eq. [1]) includes the additional terms of the roughness shift \( \Delta U^* \), \( B = \text{integral constant} \), the length scale represented by Nikuradse's equivalent sand roughness height \( k_s \), or alternatively \( z_o \) = zero-velocity level from the flume bed, and follows as:

\[
U^* = \frac{1}{\kappa} \ln(z^*) + A - \Delta U^* + B
\]  

or

\[
U^* = \frac{1}{\kappa} \ln \left( \frac{z}{k_s} \right) + B
\]

The integral constant was reported as \( B = 8.5 \pm 15\% \) for fully rough beds in Eq. [3]. For smooth and transitionally rough beds, \( B \) is a function of the roughness Reynolds number, \( \kappa^* = \frac{k_s u_\tau}{\nu} \) (Albayrak et al. 2013). The relation between \( z_o \) and \( k_s \) follows as (Nikuradse 1932, 1933; Schlichting 1979; Auel et al. 2014)

\[ k_s < 5 \quad z_o = 0.11 \frac{V_s}{u_\tau}, \quad \text{smooth bed} \]

\[ 5 < k_s < 70 \quad z_o = 0.11 \frac{V_s}{u_\tau} + 0.033k_s, \quad \text{transitionally rough bed} \]

\[ k_s > 70 \quad z_o = 0.033k_s, \quad \text{hydraulically rough bed} \]

Secondary currents of Prandtl’s second kind exist in narrow straight uniform open channel flows with \( b/h < 4-5 \) as occurring in SBTs and SFCs (Auel 2014; Müller Hagmann 2017). Such currents are driven by turbulence anisotropy, and they affect the flow by creating a 3D flow pattern (Nezu and Nakagawa 1993). The secondary currents create up-and-down flows resulting in an undulation in bed shear stress distributions, and a redistribution of the Reynolds stress and turbulence intensities across the channel (Nezu and Nakagawa 1993; Albayrak and Lemmin 2011). These 3D flow patterns and the resulting bed shear stress distributions affect sediment transport and modify channel bed-forms (Ashworth et al. 1996; Nezu and Azuma 2004; Rodríguez and García 2008; Albayrak and Lemmin 2011; Auel et al. 2014). Moreover, they cause the velocity dip phenomenon, i.e. the maximum flow velocity occurring below the surface instead of at the free surface (Nezu and Nakagawa 1993).

Previous studies on turbulence characteristics cover a wide range of flow conditions and bed properties; however, most studies are limited to low Froude numbers and high aspect ratios. Only few studies investigated supercritical flow with Froude numbers \( F = \frac{U(gh)^{0.5}}{g} > 1 \), where \( g \) = gravitational acceleration, as present in steep channels, SBTs and SFCs (Tominaga and Nezu 1992; Prinos and Zeris 1995; Li et al. 1995; Chatanantavet et al. 2013; Auel et al. 2014). There is still a lack of knowledge on the impacts of low aspect
ratios down to $b/h = 1$ on the turbulent characteristics of supercritical flows. This study aims at filling this gap by experimentally investigating the flow characteristics via conducting 2D LDA velocity measurements.

2 EXPERIMENTAL SETUP AND TEST CONDITIONS

2.1 Hydraulic model and parameter definition

The experiments were conducted in a $b = 0.20$ m wide, 0.5 m high, and 13.5 m long laboratory flume with a bed slope of $S_b = 1\%$ (Figure 1). The channel bed is lined with 20 cm thick concrete with a compressive strength of 42.2 MPa. The sidewalls are made of wood and glass, respectively. The pressurized pipe flow was converted into the supercritical free-surface flow by a jet box system developed at VAW (Schwalt and Hager 1992). The jet box is a gate controlled structure enabling to adjust the initial flow depth, $h_0$. The flow discharge $Q$ was measured using a magnetic flow meter with an accuracy of ±0.5%. The flow depth $h$ was measured at 0.5 m intervals along the flume using an Ultrasonic Distance Sensor (UDS), and a point gauge to determine the hydraulic parameters and flow non-uniformity. The roughness Reynolds number $k_r^*$ defines the hydraulic roughness of the bed, and $k_r$ was determined using logarithmic fitting. In the present set-up, the flow regime was hydraulically smooth with $k_r^* < 5$. Velocity measurements were conducted at $x = 5.40$ m in 19 vertical profiles across the flume using a 2D LDA with a 3D traverse system allowing LDA movements in streamwise, spanwise and vertical directions (Figure 1). Each profile consisted of 20 measurement points in vertical direction. The data were collected for 30 s at each measurement point, and the sampling frequencies were up to 2 kHz. Herein, five different vertical profiles named as P1-P5, where P3 is at the flume center, are presented (Figure 2).

![Figure 1. Test setup: a) experimental flume and 2D LDA system, b) flume cross-section and coordinate system](image)

Two experimental runs coded as F2 and F4 were conducted at a constant bed slope $S_b = 0.01$ with an initial water depth $h_0 = 0.10$ m, and initial Froude numbers of $F_o = 2$ and 4, respectively (Table 1). The approach flow velocity $U_o = Q/(bh_o)$ was calculated based on the continuity equation. The flow was gradually varied as $F$ decreased along the flume. Therefore, the flow parameters $F_o$, $h_0$, $U_o$, $R_o = h_0 U_o/\nu$ and $b/h_0$ at $x = 0$ differ from those at $x = 5.40$ m, i.e. $F$, $h$, $U$, $R$, and $b/h$, respectively (Table 1).

The friction velocity $u_f$ and $u_w$ were determined by applying the log-law fit (Eq. [1]), and the following equation, respectively:[1]

$$U_o = \sqrt{gR_o S_b}$$  \[8\]

where $R_o = A_w/P_w$ is the hydraulic radius with $A_w = b \cdot h = \text{wetted area}$ and $P_w = (b + 2h) = \text{wetted perimeter}$, and $S_b$ is the energy line slope. Note that the bed slope can also be used in Eq. [8] if the flow is uniform. In the data analysis, the local friction velocity $u_f$ is used. Table 1 summarizes the cross-sectional averaged values of the friction velocities, i.e. $U_f$ and $U_w$, which are in a good agreement. Therefore, Eq. [8] can be used to calculate the friction velocities if velocity data are not available.

<table>
<thead>
<tr>
<th>Table 1. Hydraulic parameters of conducted test runs</th>
<th></th>
</tr>
</thead>
</table>

2899
Table 1. Physical variables for the tests.

<table>
<thead>
<tr>
<th></th>
<th>F2</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>$F$</td>
<td>1.93</td>
<td>3.33</td>
</tr>
<tr>
<td>$R$</td>
<td>$10^5$</td>
<td>4.10</td>
</tr>
<tr>
<td>$R$</td>
<td>$10^5$</td>
<td>4.01</td>
</tr>
<tr>
<td>$Q$</td>
<td>[m$^3$/s]</td>
<td>0.041</td>
</tr>
<tr>
<td>$h_o$</td>
<td>[m]</td>
<td>0.100</td>
</tr>
<tr>
<td>$h$</td>
<td>[m]</td>
<td>0.105</td>
</tr>
<tr>
<td>$b/h_o$</td>
<td>[-]</td>
<td>2</td>
</tr>
<tr>
<td>$b/h$</td>
<td>[-]</td>
<td>1.91</td>
</tr>
<tr>
<td>$U_o$</td>
<td>[m/s]</td>
<td>2.05</td>
</tr>
<tr>
<td>$U$</td>
<td>[m/s]</td>
<td>1.96</td>
</tr>
<tr>
<td>$U_{max}$</td>
<td>[m/s]</td>
<td>2.24</td>
</tr>
<tr>
<td>$U_*$</td>
<td>[m/s]</td>
<td>0.077</td>
</tr>
<tr>
<td>$U_I$</td>
<td>[m/s]</td>
<td>0.080</td>
</tr>
<tr>
<td>$S_b$</td>
<td>[-]</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figure 2. Cross-sectional velocity measurement points (red dots) with contour plot of normalized streamwise velocities and schematic secondary current cells for F2 (+ symbol represents the maximum streamwise velocity location)

3 RESULTS AND DISCUSSION

3.1 Mean velocity profiles with logarithmic law

Figure 3a and b show the mean streamwise flow velocity profiles P1 to P5 in inner variables with the log-law fits for F2 and F4, respectively. For better visual observation, the origin $U^+ = 0$ was shifted upwards by 5 for each profile to avoid overlapping of the profiles. The vertical position of the maximum velocity $U_{max}$ is indicated by arrows in Figure 3. For all the tests, the von Kármán and integral constants were taken as $\kappa = 0.41$ and $A = 5.29$, respectively. The results show that the log-law fits the experimental data in the wall layer not only at the centerline but also in traverse locations, and it applies up to $z/h = 0.3$. The aspect ratios at $x = 5.40$ m were $b/h = 1.91$ and 1.75 for F2 and F4, respectively (Table 1). Therefore, narrow open channel flow conditions existed (Nezu and Nakagawa 1993), and secondary currents, i.e. 3D flow structures, formed. Because of such currents, the maximum velocities occurred well below the water surface (Figure 2 and 3).
Figure 3. Mean velocity profiles in streamwise direction together with the logarithmic fittings at five spanwise locations across the flume for a) F2, and b) F4 Reynolds shear stress

Figure 4a and b show the vertical Reynolds shear stress distributions normalized by $u'\bar{\nu}$ for F2 and F4, respectively, together with the universal distribution predicted with Eq. [9] for 2D flows (Nezu and Nakagawa, 1993).

$$-\frac{u'w'}{u'\bar{\nu}} = \left(1 - \frac{z}{h}\right)$$

[9]

Due to the strong 3D flow pattern, the Reynolds shear stress distributions for both F2 and F4 deviate from the linear trend suggested for the 2D flow case. Most of the turbulence generation occurs in the wall region and it reaches its maximum at $0.1 < z/h < 0.2$ (Figure 4). In the outer region of the boundary layer, the Reynolds shear stresses are negative above $z/h > 0.65$ where the velocity gradient $dU/dz$ becomes negative for both cases, independent from the Froude and Reynolds numbers. For all the profiles of F2, the data collapse well, whereas they slightly deviate from each other for F4 near the water surface. This deviation is related to the increase of the surface waviness with increasing Froude number.
3.2 Turbulence intensities

3.2.1 Streamwise turbulence intensities

The turbulence intensities $u_{rms}$ and $w_{rms}$ represent the root-mean-square values of the fluctuating velocities, $u'$ and $w'$ in the streamwise and vertical directions, respectively:

$$u_{rms} = \sqrt{u'^2}, \quad w_{rms} = \sqrt{w'^2} \quad [10]$$

Figure 5a and b show the normalized streamwise turbulence intensity profiles for F2 and F4, together with the universal distribution (Eq. [11]) proposed by Nezu and Nakagawa (1993):

$$\frac{u_{rms}}{u_*} = 2.3e^{-2.3z/h} \quad [11]$$

The present data follow Eq. [11] up to $z/h = 0.50$ for both F2 and F4 (Figure 5). Above this relative flow depth, the data deviate from Eq. [11]. The maximum streamwise turbulence intensities occur near the bed, decreasing towards $z/h = 0.7$ for both F2 and F4. At larger relative flow depths, the turbulence intensities increase towards the free water surface due to the effect of surface corner vortices in this region. The turbulence intensities at P1 and P5 are higher compared to those at P2-P4, which is related to the pronounced sidewall effect. These patterns are in a good agreement with the previous studies by Albayrak et al. (2013) and Auel et al. (2014).

![Figure 5](image_url)

**Figure 5.** Normalized streamwise turbulence intensity ($u_{rms}/u_*$) profiles for a) F2, and b) F4

3.2.2 Vertical turbulence intensities

Figure 6a and b present the normalized vertical turbulence intensity profiles for F2 and F4, together with the universal distribution (Eq. [12]) proposed by Nezu and Nakagawa (1993).

$$\frac{w_{rms}}{u_*} = 1.27e^{-1.27z/h} \quad [12]$$

In contrast to the streamwise turbulence intensities, the vertical turbulence intensities, $w_{rms}/u_*$ highly deviate from Eq. [12], showing S-shape profiles. Although Auel et al.’s (2014) data fit well with Eq. [12] for aspect ratios of 2.6 and 2.8 at the flume center line, the present data reveal significant effects of the lower aspect ratios of 1.75 and 1.95, and hence stronger secondary currents on the $w_{rms}/u_*$ distributions. The maximum values of $w_{rms}/u_*$ are around the edge of the wall region, $z/h = 0.2$, decreasing towards $z/h = 0.7$ for both F2 and F4. Above this level, the $w_{rms}/u_*$ values increase towards the water surface vortices and higher for P1 and P5 compared to those for P2-P4. These trends are similar to those observed for the streamwise turbulence intensities (Figure 6).
4 CONCLUSIONS

This paper deals with an experimental investigation on supercritical narrow open channel flows over a smooth bed simulating the flow conditions in sediment bypass tunnels. Extensive 2D LDA velocity measurements were conducted to determine the mean velocities and turbulence characteristics of supercritical open channel flows at Froude numbers $F_o = 2$ and 4, respectively. The present investigation covers rarely studied low aspect ratios of 1.75 and 1.91. The results indicate that the log-law applies in the wall region, i.e. for $z/h < 0.2$, and extends up to $z/h \approx 0.3$ for both experiments. Due to the narrow open channel flow conditions, i.e. $b/h_o < 4-5$ (Nezu and Nakagawa 1993; Auel et al. 2014), strong secondary currents occur, creating 3D flow patterns at both Froude numbers investigated. Such currents shift the maximum flow velocity from the flow surface to $z/h \approx 0.7$, which is known as ‘velocity dip phenomenon’. Similar to the velocity profiles, secondary currents re-distribute the Reynolds shear stress and turbulence intensities causing a deviation from the universal equations proposed for 2D flows.

Overall, the present results give insight into the effects of low aspect ratios with $b/h < 2$ as well as the Froude number effect on the mean and turbulence characteristics of highly supercritical open channel flows and contribute to the understanding of the interactions between the flow, sediment transport and hydro-abrasion. The follow-up study will focus on: (1) sediment transport modes for different particle size and hardness, (2) their abrasion potential on various bed materials and abrasion patterns affected by secondary flows, and (3) the development of a hydro-abrasion prediction formula.

5 ACKNOWLEDGEMENTS

The author would like to thank to Dr. Ismail Albayrak and Prof. Dr. Robert Boes for the internal review and their contributions, and acknowledge that the Swiss National Science and Foundation (SNSF) financially supports this project (Project No: 166253).

6 REFERENCES


Nikuradse, J. (1933). Stromungsgesetze in Rauhen Rohren, Forschungshefte. VDI; NACA Tech Mem, 361, 1292 (in German).


