Turbulent Characteristics and Structures Influenced by Backwater in Non-Uniform Open-Channel Flows

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ABSTRACT

The instantaneous velocity in non-uniform turbulent open channel flow in the Three Gorges Reservoir, various backwater extent has been measured by ADCP and ADV. Analyzing the mean velocity profiles, turbulence intensities, power and pre-multiplied spectra, high- and low-speed structures in various backwater extent, the results indicated that with increasing backwater coefficient, compared with the uniform-flow profiles, the distributions of mean velocity profiles show a tendency toward more concave. The high- and low-speed structures are found to alternate in the outer layer, generally similar to other turbulent flow in the laboratory. The relationship between the maximum wavelength and backwater coefficient presented a power function, qualitatively.

KEY WORDS: turbulent characteristics; large-scale turbulent structure; non-uniform open-channel flow; mean velocity profiles; pre-multiplied spectra

INTRODUCTION

Non-uniform flows are often encountered in river engineering. Knowledge of the flow structure is of importance for determining sediment transport, pollution control, and flow resistance. Over the past decades, the velocity distributions in steady and uniform flows were extensively investigated. However, only few studied experimentally the effect of non-uniformity on velocity distributions (Cardoso and Graf 1991, Kironoto and Graf 1995, Song and Chiew 2001, Yang 2009), bed shear stress (Zhang and Jin 2014, Zhang and Yang 2016). Compared with previous studies from non-uniform open channel flow, the research results focus on the mean parameters, such as velocity profiles, turbulence intensities, bed shear stress, etc. However, the research about instantaneous characteristics are comparatively few.

Transition to turbulence has remained a classical research topic in fluid mechanics for over a century since the publication of Osborne Reynolds’ landmark experiment (He and Seddighi 2013, Xu 2015). Compared with the complex, multiscaled, random fields of turbulent motion, researchers are gradually aware of the turbulence is more elementary organized motions that are variously called eddies or coherent structures. One of the most fundamental and important characteristics of wall turbulence is its strong inhomogeneity in length scales (Kovasznay and Kibens 1970, Brown and Thomas 1997, Guala and Hommema 2006).

The sediment deposition in the Three Gorges Reservoir (TGR) presented a ‘point siltation’ form with more than 90 percentage of the deposition occurring at the wide reaches and river bends in the permanent backwater region through field observations. The deposited sediments are mostly fine sediments with the median diameters less than 0.01 mm, which was not forecasted by previous studies (Li and Wang 2015). Improving understanding the relationship between turbulent characteristics, structures and fine sediments transport, therefore, field measurements were conducted at the reaches of Chongqing (at Chongqing city), Huanghuacheng (at Zhongxian town) and Chouyanqi (at Fengjie town). This work provides experimental evidence and detailed characteristics for turbulent characteristics, structures influenced by backwater.

FIELD SITES AND INSTRUMENTS

Field measurements were conducted at the reaches of Chongqing, Huanghuacheng and Chouyanqi. The Chongqing reach is 661 km away from the TGP, in Fig. 1a. The Zhongxian reach, which is approximately 350 km away from the TGP, is a meandering and bifurcation reach, as shown in Fig. 1b. The Fengjie reach is located in the famous Qutang Gorge, 160 km away from the TGP. The downstream confluence, where the Meixi River flows in, Fig. 1c.

At the Chongqing reach, 1 vertical line were arranged. At the Huanghuacheng reach, 8 cross sections were selected, and 3 or 4 vertical lines with 6 to 10 points from the water surface to the river bed on each vertical line were arranged. A total of 27 vertical lines with 193 points were measured. At the Fengjie reach, 5 cross sections were selected, and a total of 14 vertical lines with 127 points were measured.

The flow velocities are measured using ADCP and ADV. The sampling frequency of ADCP is 1 Hz, whereas that of ADV is 64 Hz. The fundamental quantities for the field measurements are stated in table 1.
Table 1 Parameters for field measurements

<table>
<thead>
<tr>
<th>Cases</th>
<th>ADCP Sample size</th>
<th>ADCP frequency</th>
<th>ADV Sample size</th>
<th>ADV frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQ1</td>
<td>8 065</td>
<td>1 Hz</td>
<td>288 736</td>
<td>64 Hz</td>
</tr>
<tr>
<td>CQ2</td>
<td>5 314</td>
<td>1 Hz</td>
<td>284 028</td>
<td>64 Hz</td>
</tr>
<tr>
<td>ZX1(S206L4)</td>
<td>16 643</td>
<td>1 Hz</td>
<td>201 600</td>
<td>64 Hz</td>
</tr>
<tr>
<td>ZX2(S205L5)</td>
<td>16 306</td>
<td>1 Hz</td>
<td>216 960</td>
<td>64 Hz</td>
</tr>
<tr>
<td>FJ1(S115L3)</td>
<td>53</td>
<td>1 Hz</td>
<td>20 000</td>
<td>64 Hz</td>
</tr>
<tr>
<td>FJ2(S115L2)</td>
<td>52</td>
<td>1 Hz</td>
<td>16 384</td>
<td>64 Hz</td>
</tr>
</tbody>
</table>

FLOW PARAMETERS AND TURBULENCE STATISTICS

Analysis flow parameters

We denote the \( i \)th component of the turbulent fluctuating velocity by \( u_i(x, y, t) \) where \( u_1 = u \) represents the streamwise component and \( u_2 = v \) represents the wall-normal component. The mean streamwise velocity profiles is denoted by \( U <U> \) represents the depth average of \( U \). In order to study the inhomogeneity of flow depth in non-uniform flow, defined backwater coefficient \( \Gamma_H \):

\[
\Gamma_H = \frac{H}{H_0} \tag{1}
\]

Where, \( H \) is the actual flow depth of backwater, \( H_0 \) as the uniform flow depth, which meet the Chezy Manning formula uniform flow, in the case of a certain discharge per unit width, roughness and slope of river bed condition.

\[
v = \frac{1}{n} \left( \frac{H}{\sqrt{\gamma H}} \right)^{2/3} \tag{2}
\]

Table 2 Hydraulic parameters for the experiments

<table>
<thead>
<tr>
<th>Cases</th>
<th>( H ) ( \text{m} )</th>
<th>( &lt;U&gt; ) ( \text{m/s} )</th>
<th>( Fr )</th>
<th>( H_0 )</th>
<th>( \Gamma_H )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CQ1</td>
<td>8.3</td>
<td>1.55</td>
<td>0.172</td>
<td>6.7</td>
<td>1.2</td>
</tr>
<tr>
<td>CQ2</td>
<td>13.7</td>
<td>0.95</td>
<td>0.082</td>
<td>6.8</td>
<td>2.0</td>
</tr>
<tr>
<td>ZX1(S206L4)</td>
<td>29.4</td>
<td>0.86</td>
<td>0.051</td>
<td>10.1</td>
<td>2.9</td>
</tr>
<tr>
<td>ZX2(S205L5)</td>
<td>34.0</td>
<td>0.90</td>
<td>0.049</td>
<td>11.3</td>
<td>3.0</td>
</tr>
<tr>
<td>FJ1(S115L3)</td>
<td>92.0</td>
<td>1.06</td>
<td>0.035</td>
<td>22.7</td>
<td>4.1</td>
</tr>
<tr>
<td>FJ2(S115L2)</td>
<td>80.2</td>
<td>0.84</td>
<td>0.030</td>
<td>18.2</td>
<td>4.4</td>
</tr>
</tbody>
</table>

Mean velocity and turbulence intensities profiles

Figure 2a shows the mean-velocity profiles of the vertical. Here the mean velocity is normalized by local \( <U> \), and the distance from the wall \( y \) is normalized by flow depth \( H \). it is noticed in Fig. 2a that with increasing backwater coefficient, the free surface velocity gradually decreases and the distributions of velocity profiles become more concave.

The turbulence intensities of streamwise velocity is scaled with \( <U> \) and plotted against \( y/H \) in figure 2b. The turbulence intensities depend on backwater coefficient, approximatively. The turbulence intensities distribution of near the wall and water surface is larger than the middle flow.

Flow mean parameters influenced by backwater coefficient

The mean velocity profiles of streamwise velocity is scaled with \( \sqrt{\gamma H} \) and plotted against \( y <U>/u \) in figure 3a. In the outer region \( (0.2H < y < 0.6H) \), the velocity profiles follow a log-law, equation (3).

\[
\frac{U}{\sqrt{\gamma H}} = A \ln \left( \frac{y}{u} \right) + B \tag{3}
\]

By fitting measured data, The slope, A, plotted against backwater coefficient \( \Gamma_H \) in Fig. 3b. Approximatively, the relationship between A and backwater coefficient is power function.
The existence of energetically significant large-scale structures in turbulent wall flow has been on a worldwide consensus. The pre-multiplied one-dimensional spectrum of the streamwise velocity measured by ADV has been analyzed in this work. The time-delayed one-dimensional cross-correlation is given by,

$$ R_{ij}(\tau) = \langle u_i(x,y,t)u_j(x,y,t) \rangle $$

The co-spectrum (cross power spectral density) is defined in terms of this correlation,

$$ S_{ij}(\omega) = \frac{1}{2\pi} \int_{-\infty}^{\infty} R_{ij}(\tau)e^{i\omega\tau} d\tau $$

To transform the spectral argument from frequency, $\omega$, to streamwise wave number, $k_x$, Taylor’s hypothesis of frozen turbulence was used, i.e., $k_x=2\pi f/U$, wherein the local convection velocity is assumed to be equal to the local mean velocity $U$.

Figure 4 shows power spectra of streamwise fluctuation velocity for different flows.

The spectrum appears to possess a $k^{-1}$ power law, as observed by Perry (1982), and it may possess a short region of $k^{-5/3}$ power law. It is generally similar to spectra obtained in other turbulent flows.

The structure of the spectrum in Fig. 4 is easier to interpret when plotted as the wave number times the spectrum, Fig. 5. Following Kim and Adrian (1999) pre-multiplied spectra of the streamwise velocity are used to identify the wavelengths $\lambda_{max}$ associated with the very-large-scale structures (lower wavenumber peak). The lower wavelength peak represents the very large scale motion wavelength carrying the highest energy density. The results have been compiled in Fig. 6.
Fig. 5 Pre-multiplied power spectra of streamwise velocity fluctuation

Fig. 6 Relationship between Backwater coefficient and $\lambda_{\text{max}}/H$

Kim and Adrian (1999) conclude that the wavelength of the very large scale motion is approximately 12-14 times the pipe radius, in the outer layer of fully developed turbulent pipe flow. Also, Balakumar and Adrian (2007), Zhang and Yang (2015) indicated that the wavelength of very large scale motion is about greater than 10 times the flow depth (boundary-layer thickness). The variations in the wavelengths $\lambda_{\text{max}}/H$ are plotted versus the backwater coefficient for various flows in Fig. 6. The maximum wavelength of very large scale motion is 12.2 times the flow depth in case CQ1 at lower backwater coefficient. It is generally similar to distribution obtained in other pipe flows, and in channel flow and boundary layers. Generally, the values of $\lambda_{\text{max}}/H$ decreases with increasing backwater coefficient. By fitting measured data, the relationship between the maximum wavelength of pre-multiplied spectra peaks and backwater coefficient is power function, approximatively.

**Large scale high- and low- speed structures**

The existence of energetically significant large-scale structures in turbulent wall flow was recognized by Adrian and Meinhart (2000), Hommema and Adrian (2003), Elsinga and Adrian (2010), Dennis and Nickels (2011), Yang and Zhang (2016), etc. The high- and low-speed structures are important, and dominant feature of wall turbulence. This work shows that the large-scale streamwise high- and low-speed structures are the primary factor that alters the features of the instantaneous flow structures. The velocities were measured by ADCP.

Contour plots of the streamwise fluctuating velocity show very long high- and low-speed structures in whole flow depth, in Fig. 7. Generally, high- and low-speed structures are found to alternate in the various backwater coefficient. The streamwise average length of high-speed or low-speed structures is about 10 times the flow depth in case CQ1 at lower backwater coefficient. The height of high-speed or low-speed structures is approximately equal to the flow depth. With increasing backwater coefficient, the scale of high-speed (low-speed structures) is rapidly decreasing. This results are consistent with the pre-multiplied spectra of the streamwise velocity obtained by ADV.

**CONCLUSIONS**

The instantaneous, three-dimensional velocity in non-uniform turbulent open channel flow in the TGR, various backwater extent has been measured by ADCP and ADV. The results present a visualization of the flow structures in the outer layer, and the relationship between turbulent characteristics, structures and backwater coefficient. The following conclusions can be drawn:

1. With increasing backwater coefficient, compared with the uniform-flow profiles, the distributions of mean velocity profiles and turbulence intensities show a tendency toward more concave at around $0.6H$ and waning, respectively.
2. At lower backwater coefficient, the energy spectra for non-uniform flows in natural river are essentially the same as for uniform flow. The high- and low-speed structures are found to alternate. It is generally similar to other turbulent flow in the laboratory.
3. The relationship between the maximum wavelength ($\lambda_{\text{max}}/H$), slope (A) and backwater coefficient presented a power function, qualitatively.

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