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Characterization of Double-Averaged Velocity Profile in an Open-Channel With Intermediate Relative Roughness

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ABSTRACT: Flow with intermediate relative roughness (the ratio of roughness height to water depth higher than 1/80 and lower than 1/40) is common in most of the mountainous streams. Despite this fact and numerous studies on flow with intermediate relative roughness, it is still unclear how the profile of the streamwise velocity varies along with water depth. In this study, the instantaneous velocity of flow in an open-channel with the rough bed has been measured using Particle Image Velocimetry (PIV). In order to analyze the profile of streamwise velocity, double averaging method (spatial averaging of time-averaged values in a thin slab parallel to the channel bed) was used. It was observed that near the rough bed, vectors of instantaneous velocity showed strong spatial variations that make extraction of unique behavior for velocity profile impossible without double averaging. Results also showed that values of double averaged velocity were not sensitive to priority in averaging (i.e. time and then spatial averaging or spatial and then time averaging); thus double averaging regardless of priority can be used. To investigate double averaged velocity profile, three approaches including a logarithmic profile with a variable parameter, linear profile and mixing layer profile were employed. Results showed that all three profiles could be fitted properly to our experimental data. However, logarithmic profile with variable Von-Karman constant and integration constant that was supported by strong scientific background was the most suitable profile and therefore can be recommended.

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1. INTRODUCTION

A rough bed is a sort bed geometry condition in which protrusions of bed elements on flow structure cannot be neglected. Concerning rough bed flow in open-channels, Nikora et al. [1] identified four flow types depending on the relative submergence (or relative roughness). Based on this approach, four types of flow can be considered which are low relative roughness flow ($H/\ \Delta<1/80$), intermediate relative roughness flow ($1/80<H/\Delta<1/5$), high relative roughness flow ($1/5<H/\Delta<1$), and partially inundated flow. Although intermediate relative roughness flow is common in nature, the knowledge on such flows remains limited in spite of the recent advances [2, 3].

Previous studies showed that in intermediate relative roughness flow, spatial variation of near-bed flow characteristics is too high, which makes extraction of unique behavior almost impossible. To resolve this problem, the time averaging of the governing equations should be supplemented by spatial averaging in a plane parallel to the mean bed surface. After such an averaging, a new system of equations will be obtained which are known as double averaged, or spatially averaged Navier-Stokes equations [1].

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Concerning double-averaged streamwise velocity profile in intermediate relative roughness flow, three approaches are common. The first approach is based on the logarithmic profile with variable Von-Karman constant and constant of integration [2]. In the second approach, a linear profile is fitted to the double-averaged velocity values [1]. Finally, in the third approach, the double-averaged velocity is considered as a mixing layer profile [4]. In the present study, we studied the velocity profile in intermediate relative roughness flow. To this end, the instantaneous velocity was measured in an open-channel. The details of these measurements will be explained in the following section.

2. METHODOLOGY

Laboratory measurements were conducted in an open-channel 14 m long, 0.75 m wide and 0.7 m deep in Hydraulic laboratory of Amir Kabir University. The flow depth and discharge at the flume inlet were controlled by an inverter for pump speed regulation and was measured by an electromagnetic flowmeter.

Hydraulics characteristics of these measurements are summarized in Table 1. As reported in this table, three experimental runs cover an appropriate range of flow with

Table 1. Hydraulic characteristics of the present study.

H **(m)**	**Run1**	**Run2**	**Run3**
$\Delta=D$ (m)	0.1	0.12	0.15
R (m)	0.015	0.015	0.015
Fr	0.079	0.091	0.107
Rr	0.08	0.06	0.04
D/H (-)	8000	8000	8000
B/H (-)	0.15	0.125	0.1
Q (lit/s)	7.5	6.25	5
L_{FD} (m)	6	6	6
S_f (-)	3.46	3.29	2.88
u_* (m/s)	0.00005	0.000048	0.000046
H (m)	0.008	0.007	0.007

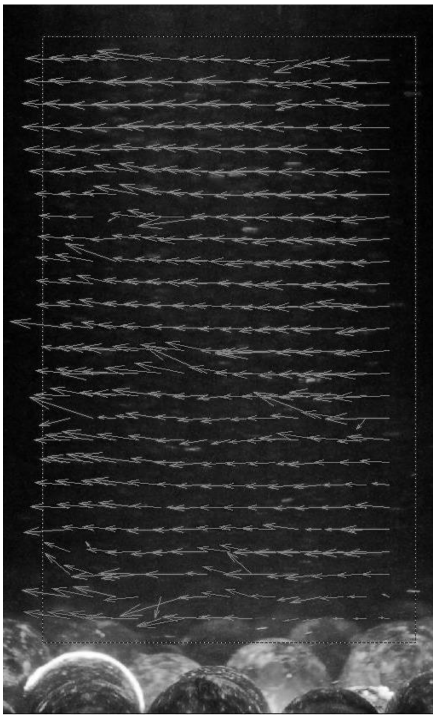

Fig. 1. Instantaneous velocity vectors, flow from right to left.

intermediate relative roughness. The channel bed was roughened using crushed stone (in an area far from the measurement section) and glass sphere with a diameter of 15 mm. In this study, roughness height and vertical bed origin were respectively considered as glass sphere diameter and the crest of the glass sphere.

Measurements were performed in a region at least 150 mm far from both sidewalls at the distance of 7.0 m from the entrance of the channel, where the velocity profile is fully developed. To measure streamwise velocity, PIV measurements in vertical planes were carried out. The

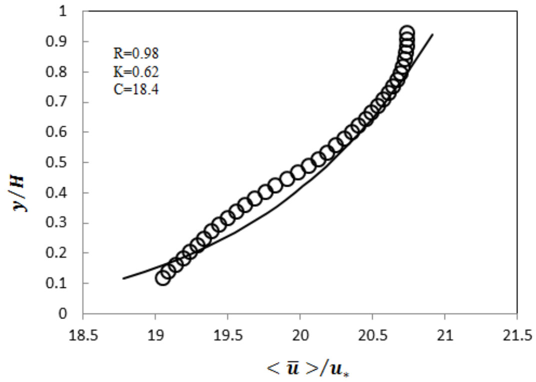

Fig. 2. Results of fitting logarithmic profile to Run1.

image analysis and processing were performed with PIVLab software. The flow was sampled for 3 min with a frequency of 60 Hz. The acquisition area was approximately 360 px long and 360 px wide which leads to 5 mm vector spacing.

3. DISCUSSION AND RESULTS

In Figure 1, vector maps of instantaneous velocity in the vertical measurement plane are shown. This figure shows that velocity vectors of the near-bed region show strong spatial variations, while in a region far from rough bed such strong variation attenuates. This observation is in agreement with previous studies that also showed that the near-bed velocity field is highly affected by bed topography [2].

We also compared the profiles of space-time and time-space double-averaged streamwise velocity. According to this comparison (not shown in English abstract), the double averaged velocity profile was not sensitive to the priority of averaging and time-space averaged and space –time-averaged profiles were almost identical to each other.

In the next step, double-averaged profiles of streamwise velocity explored. In Figure 1, the results of fitting logarithmic profile to Run1 data are shown. As reported in this Figure, the profile is fitted very well to the experimental data with near one value of determination coefficient (*R*). However, it was observed that obtained value for Von-Karman constant (*k*) and integration constant (*C*) was different from common values. Similar results were also seen for Run2 and Run3. These observations are in agreement with observations of Koll et al. [4] and Mohajeri et al. [2] who also reported similar observation. Indeed, previous studies showed that these parameters for flow with intermediate relative submergence are variable respect to relative roughness. Comparison of observed values for Von-Karman constant in this study with previous studies showed that except Run2, the observed values are in the range of the reported values in the literature.

We also explore the accuracy of the linear profile and mixing layer profile in intermediate relative roughness flows. It was notified that both of these approaches could fit perfectly with our experimental data. However, fitting linear to this type of flow suffers from a good scientific background and it is not rational to consider this profile at least for lower values of relative roughness. As regards of mixing layer profile, it was observed that the profile could fit properly to our data with not acceptable values for parameters of this equation such as characteristic energetic eddy size. Therefore, it can be recommended that in future studies the logarithmic approach should be followed for this type of flow.

4. CONCLUSIONS

The present study focused on the flow structure of intermediate relative roughness flow using the double-averaging method. The main finding in this study can be itemized as:

1- Near the rough bed, flow showed strong spatial variation which makes the study of this type of flow without double-averaging almost impossible.

2- Comparison of space-time averaged and time-space averaged velocity profiles showed that there was no any advantageous in priority of space or time averaging.

3- This study also showed that the logarithmic layer approach with variable Von-Karman constant and integration constant was the best approach for double-averaged velocity profile of flow with intermediate relative roughness.

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