Scientia Iranica A (2018) 25(4), 1956–1967

SCIENTIA IRANICA

Sharif University of Technology
Scientia Iranica
Transactions A: Civil Engineering
http://scientiairanica.sharif.edu

Importance of bed roughness in transversal variability of the flow patterns and bed shear stress due to secondary currents

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Received 5 June 2016; received in revised form 7 January 2017; accepted 4 February 2017

KEYWORDS
Rough bed;
Turbulent flow;
Flow variability;
Open channel;
Secondary current.

Abstract. Laboratory experiments were carried out in order to study the influence of bed roughness on secondary circulations and lateral flow variability in a straight open channel. Flow field and bed shear stress were measured using an acoustic Doppler velocimeter and a particular type of the Preston tube, respectively. All experiments attested to the presence of noticeable lateral variations of the flow characteristics due to the secondary currents. The observations also revealed that the lateral variations in the experiments with larger bed roughness were more intense. This implies the formation of a more stable mechanism for the maintenance of the cellular pattern in the experiments with larger bed roughness elements. Regarding formation of the secondary currents, application of double averaging method (averaging of the time averaged turbulence parameters within a thin spatial slab parallel to the bed) is also discussed. It was found that, to properly consider the lateral variations of the flow characteristics, spatial averaging should be implemented among the measured data at different spanwise locations. As such secondary current enhancements can affect more complex and natural flows, like river flows, it can also be recommended to examine the importance of these phenomena in those areas with respect to double averaging method.

1. Introduction

Study of open-channel turbulent flow over rough bed is beneficial to provide better understanding of many riverine physical processes. For example, sediments dynamics arise from turbulent fluctuations of velocity [1-4] in transport and diffusion of pollutants and nutrients; also, surface-subsurface exchanges are mostly triggered with turbulent momentum fluxes [5-7] and the dam break flood waves propagation can be affected by floodplain roughness [8]. Moreover, natural rough bed elements such as pebbles or cobbles create noticeable drag force, which could modify flow resistance [9,10]. Indeed, the knowledge of rough bed turbulent flow has a significant effect on sustainable environmental management of the mountainous rivers.

River and open-channel turbulent flows can be considered as a specific type of the boundary layer flows, which contains three-dimensional turbulent flow structures [11,12]. In such circumstances, large-scale streamwise counter-rotating vortical struc-

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doi: 10.24200/sci.2017.4204

tures are formed along cross-section, which are known as Prandtl's second kind of secondary currents or turbulent-driven secondary currents [13-15]. Environmentally, turbulent secondary currents are important as they cause lateral undulation of the flow characteristics along the whole flow depth [14]. As a result of secondary currents, along cross-section, upwelling and down-welling regions are formed, which can significantly affect the near-bed sediment erosion and deposition [16,17]. Also, in such conditions, many other biological and physicochemical processes associated with the flow characteristics, such as self-aeration, heat, gas, and momentum exchanges, can be significantly influenced [15,18].

Formation of the secondary currents in rectangular open channels is attributed to the effects of side walls [19]. If the channel width is small, i.e., the side walls are not too far from each other, secondary currents are formed in the whole cross-section. Accordingly, based on the channel's aspect ratio (which is defined as the ratio of channel width to water depth, i.e., B/H), Nezu and Nakagawa [14] classified the rectangular open channels: The first class was called narrow channels, which had aspect ratios smaller than 5. In narrow channels, secondary currents are present in the whole cross section. The second class was wide channels, where B/H was larger than $2.5 \sim 5$. In this category, no secondary currents are formed in the central part of the channel (i.e., $y/(H > 2.5)$, where y is transversal location) and, therefore, flow characteristics do not noticeably undulate in the lateral direction.

In the case of rough-bed open-channel flow, it has been observed that protrusions of the roughness elements produce a spatially complex, three-dimensional structure, which leads to the heterogeneity of near-bed flow characteristics [20,21]. Since, in spatially heterogeneous flows, formation of secondary currents is more probable [13,15], one expects the secondary currents may also be enhanced. Studies of rough-bed flows in wide open channels in 1970s and 1980s showed the absence of the secondary currents in the central zone [14]. For instance, Nezu and Rodi [17] did not find any clear secondary currents in the central zone of a wide channel with the aspect ratio equal to 10. Although it was assumed that in the central part of the wide channels, secondary currents could not be formed, further studies showed that in wide open channels with rough bed, flow characteristics could laterally vary due to the formation of secondary currents. Experimental results of Nikora et al. [22] with $B/H = 6.15$ showed that in the central zone of the channel ($y/(H > 2.5)$), slight variation of flow characteristics was still noticeable. Also, Rodríguez and García [23] showed that in rough-bed flows with aspect ratios higher than 5 ($B/H = 6.3, 8.5$), secondary currents were formed. In another study, measurements of Cooper and Tait [24] in horizontal plane just above gravel crests ($B/(H = 5 \sim 20)$) showed longitudinal strips of low and high values of the streamwise velocity along the whole cross-section. These strips could also be imprints of secondary currents present in the central zone of the wide channel. Similar findings were also reported by Blanckaert et al. [25]. Blanckaert et al. [25] concluded that secondary currents could be sustained over the entire width if the roughness was sufficient to provide the required transverse oscillations in the bed shear stress and the turbulent shear stresses. Albayrak and Lemmin [12] in the case of very wide open channels ($B/(H = 12 \sim 20)$) reported the presence of lateral variation of the flow characteristics out of the near side wall region. Recently, Mohajeri et al. [26] depicted the presence of the longitudinal low-momentum and high-momentum strips in the time-averaged velocity field induced by secondary currents in a gravel-bed open channel ($B/(H = 6.7 \sim 10)$).

It is clear that the extension of the secondary currents toward the central zone is attributed to the bed roughness. However, many aspects of this effect have not been well described [27]. For instance, the role of roughness elements size on the secondary currents is not well defined. In fact, it is not clear how transversal variations of the flow characteristics change with roughening of the channel bed and, consequently, how secondary currents are enhanced over the channel width. In the present study, the role of bed roughness on the transversal variation of the flow characteristics is highlighted. Specifically, transversal variations of the flow field and turbulent characteristics, such as streamwise velocity, Reynolds stresses, and bed shear stress, are studied through possibility of secondary currents formation.

2. Experimental setup

The laboratory experiments were conducted in a straight rectangular flume, 11 m long and 1 m wide (Figure 1(a)), at the Hydraulic Laboratory of Tarbiat Modares University. The channel side walls and bed were respectively made from glass and smooth Perspex. Free surface profiles were measured with an ultrasonic distance transducer to control the condition of flow uniformity. To regulate the flow depth and stabilize uniform flow condition, a fully automated flap weir was installed at the end of the flume. Small surface waves at the entrance of the flume were eliminated using a 1.5 m long, 0.95 m wide polystyrene plate held parallel to the upper water surface right at the end of the water intake. The flow rate was controlled with a gate valve and measured by means of a magnetic flow meter.

During experiments, four different hydraulic scenarios were performed in subcritical flow condition. A summary of the experimental conditions is reported in

Table 1. In this table, S is channel slope, $\mathrm{Re} = UH/v$ is Reynolds number with U cross section averaged streamwise velocity and v kinematic viscosity, and $\mathrm{Fr} = U/\sqrt{gH}$ is Froude number with g gravitational acceleration and Q water discharge. Values of Re show that the measured flows are completely turbulent. Also, Froude number intentionally maintains an almost constant value, which is similar to the observed Froude number in natural gravel bed flow. Shear velocities (U_*) in Table 1 are estimated simply based on the energy slope method ($U_* = \sqrt{gR_H S}$ where R_H is hydraulic radius). Aspect ratios for all measurements were kept in the range of wide channels, i.e., $B/H = 6.2, 7.2$ [14]. The dimensionless Nikuradse equivalent roughness ($k_s^+ = k_s U_*/v$ where k_s is Nikuradse equivalent roughness) is higher than 70 (Table 1), showing that measurements are in hydraulically rough bed conditions [14]. Also, k_s^+ covers a wide range of values (from 86 to 188), which allows us to explore importance of the roughness characteristics in the lateral variation of the flow characteristics. Measurements were carried out at a test section located 7 m downstream from the channel entrance (Figure 1(a)), where the flow was fully developed. The full development of the flow in measurement section was also controlled by comparison with the formula proposed by Nikora and Goring [22] for full development length. The estimated values of the full development length (X_L) from the formula of Nikora and Goring [22] are reported in Table 1.

Two series of the crushed stones were randomly spread in the bottom of the channel from the entrance to the end (Type 1 roughness: $D_{90} = 0.47$ cm, $D_m = 0.31$ cm; Type 2 roughness: $D_{90} = 0.95$ cm, $D_m = 0.7$ cm, where D_{90} is the grain diameter at 90% passing and D_m is the mean diameter of the particles). To assure that the bed was immobile, crushed stones were glued to the bottom of the channel. The final random rough bed in the case of Type 2 is shown in Figure 1(b). The standard right-handed x, y, z coordinate system is used in this study. The x-coordinate is oriented in streamwise direction, spanwise direction is y-coordinate, and normalwise direction is z-coordinate, measured from the channel bed. In the present study, vertical position of the bed is assumed to

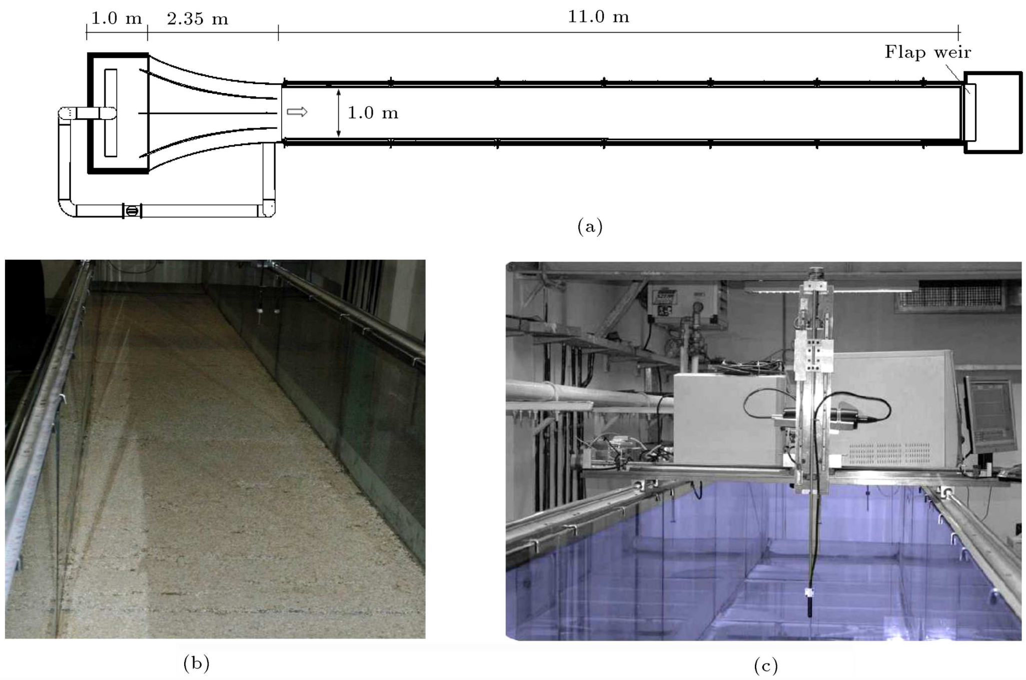

Figure 1. Experimental setup: (a) Plan view of the open channel, (b) roughness elements at the bottom of the open channel, and (c) velocimeter accompanied by the traversing system.

Table 1. Hydraulic parameters in experimental measurements.

Exp.	$S(-)$	H (cm)	U_* (cm/s)	Re	Fr	Q (lit/s)	k_s^+	B/H	D_{90} (mm)	X_L (m)
H13R1	0.0003	13	1.95	26.9 10^3	0.23	33.89	86	7.7	4.75	5.3
H13R2	0.0003	13	1.95	24.3 10^3	0.2	30.7	173	6.2	9.5	4.8
H16R1	0.0003	16	2.17	35.3 10^3	0.23	46.68	94	7.7	4.75	6.5
H16R2	0.0003	16	2.17	32.1 10^3	0.2	42.43	185	6.2	9.5	5.9

be in the top of the roughness elements and Nikuradse equivalent roughness is assumed to be D_{90} as suggested by Nikuradse [28].

Flow field was measured by a vectorino type 10 MHz down-looking micro-Acoustic Doppler Velocimeter (ADV) capable of measuring instantaneous three velocity components. The micro-ADV was installed on an automated-traversing system, as shown in Figure 1(c). The velocity measurements were done at a sampling rate of 100 Hz over a 45-mm^3 sampling volume. Each velocity point was sampled for at least 300 s to assure that the number of independent samples was enough for statistical analysis. Due to the inefficiency of the down-looking probe at the near free surface layers, the upper 5.5 cm of the flow could not be measured. In normalwise and spanwise directions, the distances between two consecutive measurement points were respectively 5 cm and 5 mm. Measurements were performed in only half of the channel, after verifying symmetry of the velocity distribution with respect to the channel centerline.

In addition to the flow field, local bed shear stresses were measured using a homemade Preston tube named three-tube device in the present study [29]. The in strument consisted of three total pressure probes and one static probe (Figure 2), which was used to evaluate shear velocity in both smooth and non-smooth wall conditions [29]. From three-tube device, the shear velocity can be obtained using the following equation, which is extracted from the wall-similarity approach [30]:

$$\frac{1}{u_*} = \frac{[8\rho(P_2 - p)]^{0.5}}{\kappa(a_{12} + a_{23})} \left[\frac{a_{12}}{\Delta_{12}} - \frac{a_{23}}{\Delta_{23}} + \frac{a_{12} + a_{23}}{4(P_2 - p)}\right], \quad (1)$$

where ρ is density, a_{12} and a_{23} are the vertical distances between the first and second total pressure probes and second and third total pressure probes, respectively, and p is the static pressure measured in the level of the second total pressure probe; moreover, $\Delta_{12} = P_1 - P_2$ and $\Delta_{23} = P_2 - P_3$ with P_i total pressure at tube ith. Based on Eq. (1), local shear stress can be determined without any assumptions or limitations regarding bed roughness and the distance of the measuring tube from the bed. The manufactured probes were connected to four capacitive types, Keller 41X pressure transducers, using silicon tubes and, thus, the collected data could be stored in the computer. Each point measurement with three-tube pressure instrument was continued for around 300 s similar to the measurement of the velocity field, while three-tube pressure instrument data were measured with the frequency of 50 Hz. More detailed information concerning three-tube pressure instrument can be find in [29].

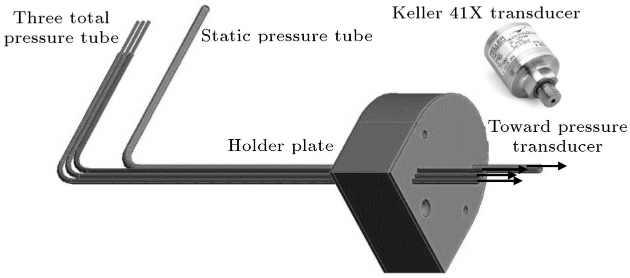

Figure 2. Details of three tube device elements used for measurement of shear stress.

3. Results

In Figure 3, contour-maps of the dimensionless streamwise velocity ($\bar{u}/u_*$) in different transversal locations are shown. In this figure, while flow field is measured in half of the cross-section, for a better visualization, contour-maps of the streamwise velocity are mirrored with respect to the channel centerline. In all measurements in Figure 3, lateral variation of the streamwise velocity is noticeable. Several pairs of low- and high-velocity regions can be clearly seen in the contour-maps of each experiment. The transversal spacing between the centers of two consecutive low-velocity zones (Δ) is approximately constant and scaled with water depth. However, looking deeper at Figure 3, one can see that transversal spacing in Figure 3(a) and (b) (i.e., measurements in $H = 13$ cm and $B/H = 7.7$) is slightly higher than that in Figure 3(c) and (d) (i.e., measurements in $H = 16$ cm and $B/H = 6.2$). More specifically, lateral spacing in Figure 3(a), (b) is $\Delta = 2.2H$, while in Figure 3(c) and (d), lateral spacing is $\Delta = 1.9H$. The observed values for transversal spacing are approximately in agreement with the observation of Albayrak and Lemmin [12], who scaled this lateral spacing with two times the water depth. Comparison of the measurements with different water depths, but with the same rough bed condition, shows that positions of the low- and high-velocity regions are approximately constant. As an example, in Type 1 roughness measurements, non-dimensionless transversal positions of the low- and high-velocity regions in H13R1 measurement (Figure 3(a)) and H16R1 measurement (Figure 3(c)) are consistent. On the other hand, comparison of the measurements with the same aspect ratio, but different rough bed conditions, reveals that transversal oscillation of the streamwise velocity is intensified in the cases with higher roughness. In fact, velocity measurements above Type 2 rough bed (Figure 3(c) and (d)) show stronger variation than those above Type 1 rough bed do (Figure 3(a) and (b)).

To better compare the transversal undulation of the streamwise velocity with the logarithmic profile, profiles of dimensionless mean streamwise velocity in different transversal locations are shown in Figure 4. In this figure, the conventional logarithmic law for rough

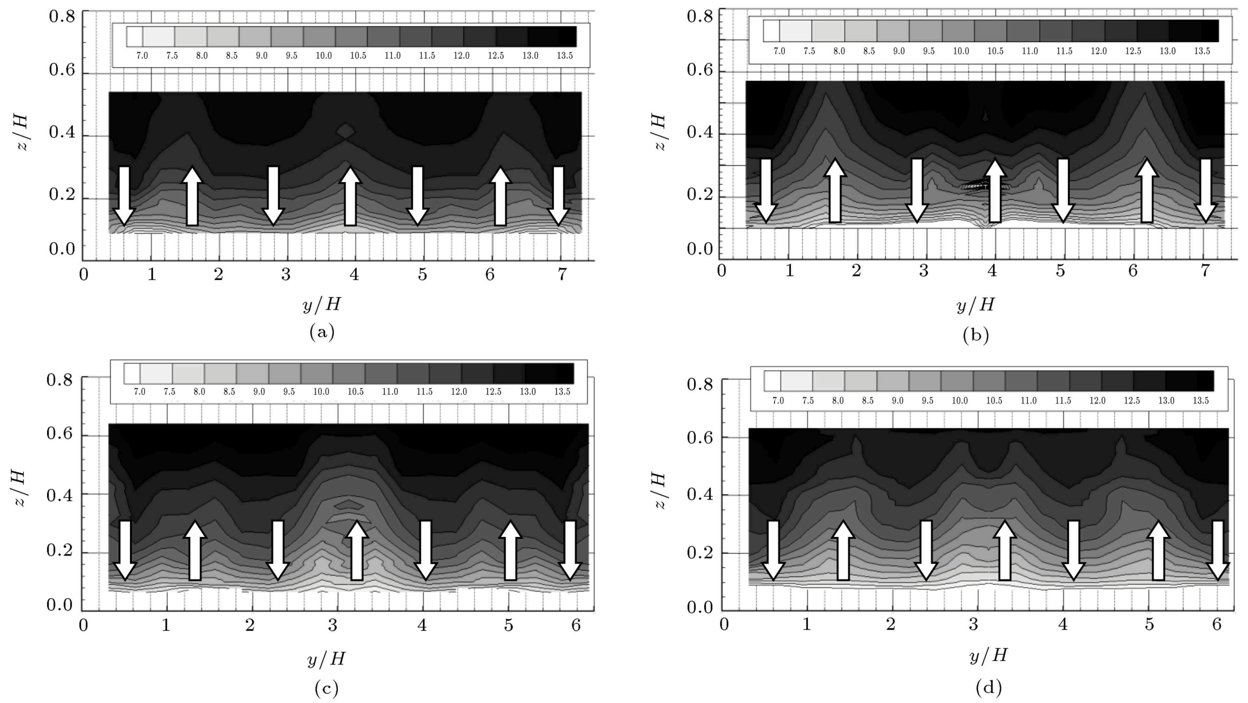

Figure 3. Contour plots of the streamwise velocity component for (a) H13T1, (b) H13T2, (c) H16T1, and (d) H16T2.

bed, based on the following equation, is also shown:

$$\frac{U}{U_*} = \frac{1}{\kappa} \ln\left(\frac{z}{k_s}\right) + 8.5, \qquad (2)$$

where κ is von Kàrmàn contant, which is 0.41 in the case of open-channel flows [14,31]. Mean streamwise velocities in Figure 4 are fairly in agreement with logarithmic law, irrespective of the transversal locations of the measurements. A more detailed investigation into Figure 4 shows that the differences between theoretical line and experimental data in larger roughness (Figure 4(b) and (d)) are higher than those in smaller roughness (Figure 4(a) and (b)). In particular, the mean value of relative difference between theoretical line and experimental data ($100|U_{\log} - U_{\exp}|/U_{\log}$ where $U_{\log}$ is the value obtained from Eq. (2) and $U_{\exp}$ is experimental mean streamwise velocity) in Type 1 roughness (7% and 4%, respectively, in H13T1 and H16T1 measurements) is smaller than that in Type 2 roughness (16% and 10%, respectively, in H13T2 and H16T2 measurements).

The lateral variation is also observed in the second order moments. These observations are reported in Figures 5 and 6. In Figure 5, profiles of Reynolds shear stress normalized by shear velocity ($\overline{u'w'}/u_*^2$) in different transversal locations are shown. To compare the experimental results with theoretical values, the linear profile of Reynolds shear stress, derived from two-dimensional flow assumption, is also shown. This equation is as follows [14]:

$$-\overline{u'w'} = U_*^2(1 - z/H). \qquad (3)$$

In Figure 5, as expected from Eq. (3), the data of all experiments increases from water surface toward the bed in a linear trend. However, depending on the transversal position of the measurement, values of $-\overline{u'w'}/U_*^2$ can be higher or lower than Eq. (3). There is also a consistency between lateral variation of Reynolds shear stress and streamwise velocity variation (Figure 4). The values of Reynolds shear stress are higher than the values expected for 2D flows (Eq. (3)) in the regions with lower streamwise velocities (e.g., $y/b \approx 0.2, 0.5$ in Figure 5, which corresponds to $y/H \approx 1.25, 3.1$ in Figure 3(a) and (b) and $y/H \approx 1.5, 3.9$ in Figure 3(c) and (d)) and lower than Eq. (3) in higher streamwise velocity regions (e.g., $y/b \approx 0.1, 0.4$ in Figure 5, which corresponds to $y/H \approx 0.7, 2.9$ in Figure 3(a) and (b) and $y/H \approx 0.6, 2.3$ in Figure 3(c) and (d)). To better see this relevancy, in Figures 5 and 6 as well as in the figures, like Figure 7, the points corresponding to high streamwise velocity are shown with filled symbols, while hallow symbols refer to the area with lower streamwise velocity. Moreover, it seems that the profiles of Reynolds shear stress with higher values have nearly convex distribution, while profiles of Reynolds shear stress with lower values have nearly concave distribution. Similar results are reported in the previous studies. Nezu and Nakagawa [19] found that in the up-welling region with lower streamwise velocity, the deviation of Reynolds shear stress was positive and convex distribution was formed. In the down-welling region with higher streamwise velocity, the deviation of Reynolds shear stress was negative and concave distribution was formed. This finding is

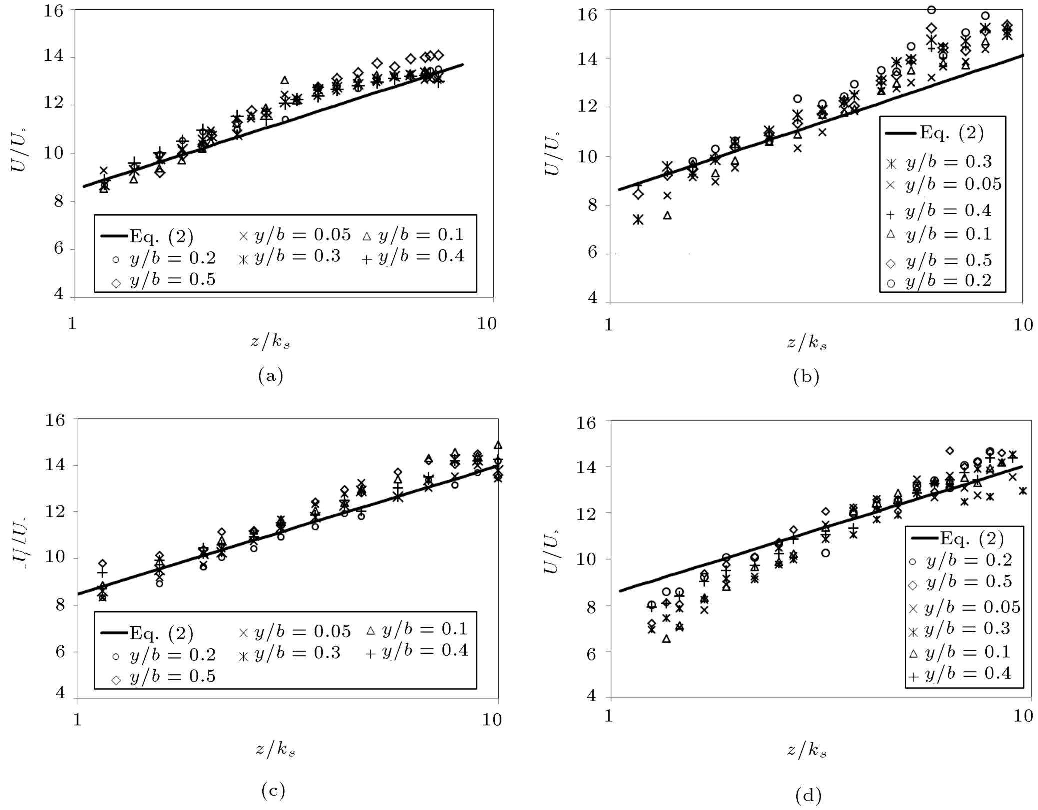

Figure 4. Dimensionless streamwise velocity profiles for (a) H13T1, (b) H13T2, (c) H16T1, and (d) H16T2.

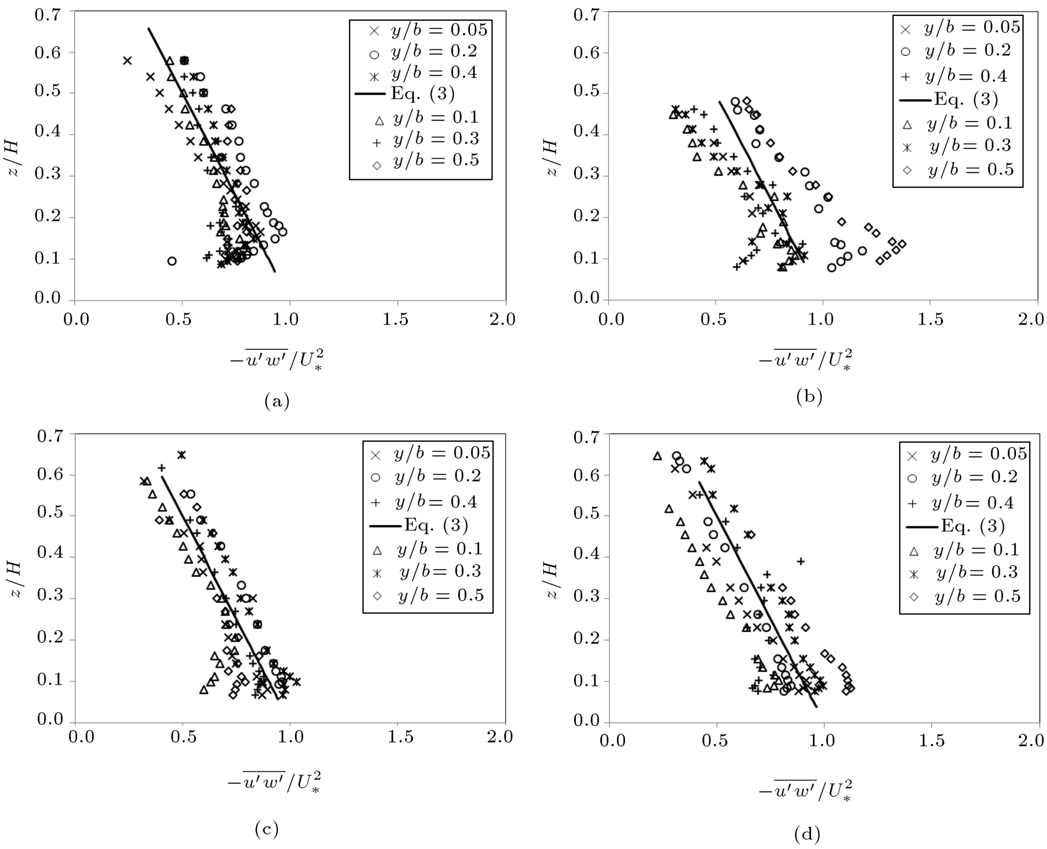

Figure 5. Dimensionless Reynolds shear stress profiles for (a) H13T1, (b) H13T2, (c) H16T1, and (d) H16T2.

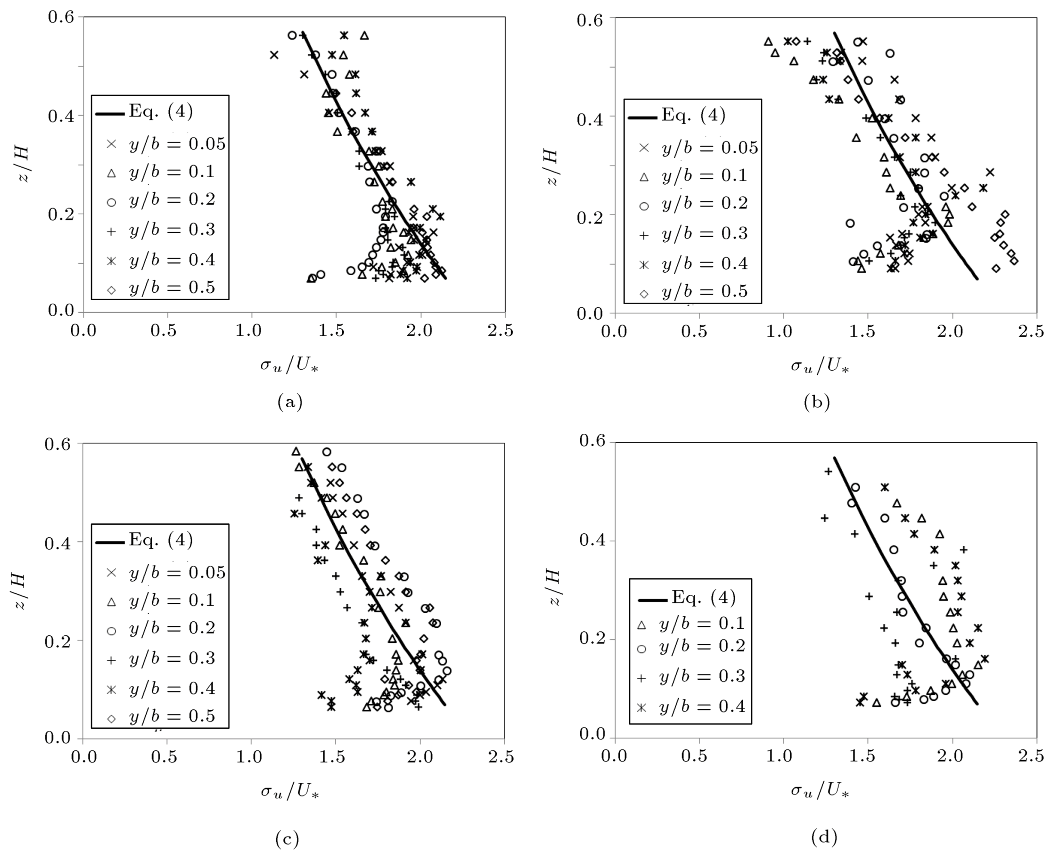

Figure 6. Dimensionless streamwise turbulence intensity profiles for (a) H13T1, (b) H13T2, (c) H16T1, and (d) H16T2.

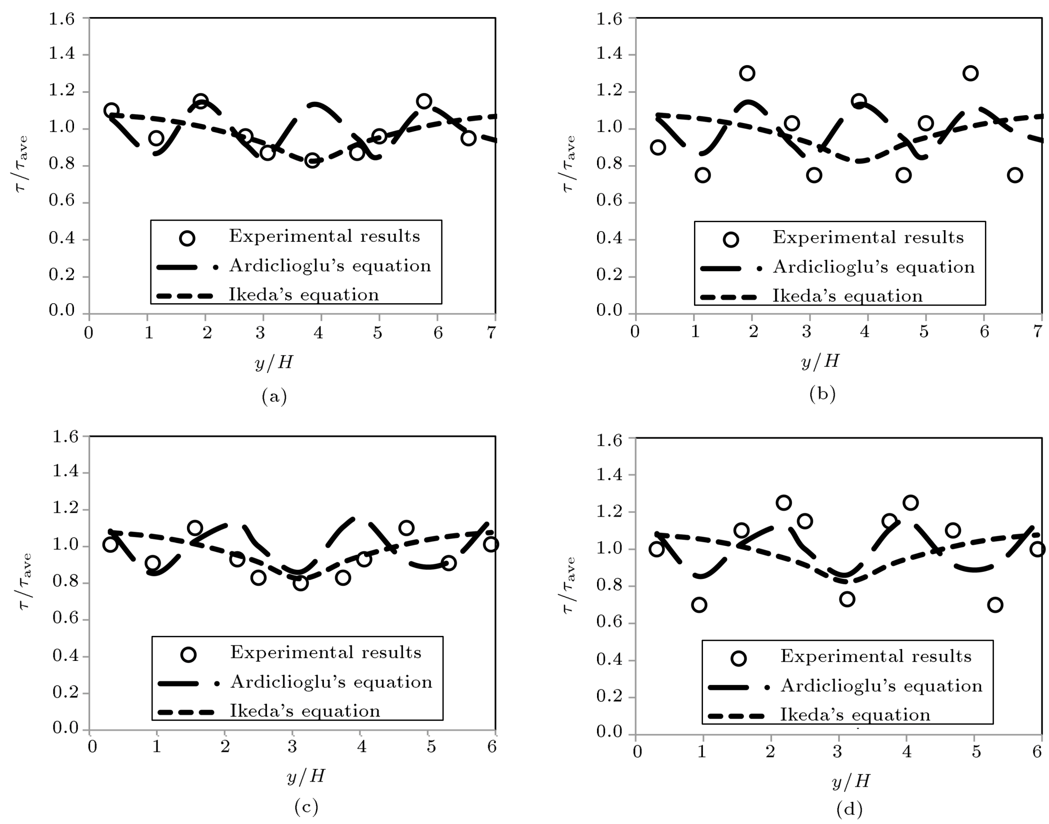

Figure 7. Bed shear stress variations over cross-section for (a) H13T1, (b) H13T2, (c) H16T1, and (d) H16T2.

in agreement with the experiments of Albayrak and Lemmin [12] in the channel with very high aspect ratio. Another important point concerning the results in Figure 5 is the intensity of Reynolds shear stress variation in transversal direction. Transversal variation of Reynolds shear stress in Type 2 measurements (Figure 5(b) and (d)) is stronger than that in Type 1 measurements (Figure 5(a) and (c)). In other words, like mean streamwise velocity, transversal variation of Reynolds shear stress is more significant when bed roughness is higher.

Figure 6 shows transversal variation of streamwise turbulent intensity. For comparison, the equation of Nezu and Nakagawa [14] is used. This equation is as follows:

$$\frac{\sigma_u}{U_*} = 1.27\exp\left(\frac{-z}{H}\right), \qquad (4)$$

where σ_u is streamwise turbulent intensity. The streamwise turbulent intensity variation along water depth is in agreement with Eq. (4). This means that streamwise turbulent intensity increases from near-free surface toward the bed. However, the values of streamwise turbulent intensity are different from the values predicted by Eq. (4). The values of streamwise turbulent intensity are higher than Eq. (4), where streamwise velocity is low and Reynolds shear stress is higher than the linear profile. Besides, the values of streamwise turbulent intensity are lower than Eq. (4), where streamwise velocity is high and Reynolds shear stress is lower than the linear profile (note the filled and hollow symbols). Concerning the intensity of variation in lateral direction, it is found that transversal variation of streamwise turbulent intensity in Type 2 measurements (Figure 6(b) and (d)) is stronger than that in Type 1 measurements (Figure 6(a) and (c)), i.e., stronger variation in the case of higher roughness.

Finally, in Figure 7, lateral variation of bed shear stress obtained from three-tube device is shown. Similar to Figure 4, in this figure, for a better visualization, the data is also mirrored with respect to the channel central line. Shear stress for each measurement is normalized with averaged value of shear stress in the measurement cross-section. The data is compared with the equation proposed by Ikeda [32]:

$$\frac{\tau}{\tau_{\text{ave}}} = 1 + \delta\cos\left(\frac{\pi y}{H}\right), \qquad (5)$$

where τ is shear stress, τ_{ave} is average shear stress in cross-section, $\pi = 3.14$, and δ is a constant equal to 0.15 [32]. In addition to the equation of Ikeda [32], the equation of Ardiclioglu et al. [33] is used for comparison. This equation is as follows:

$$\frac{\tau}{\tau_{\text{ave}}} = -0.247\left(\frac{2y}{B}\right)^2 - 0.007\left(\frac{2y}{B}\right) + 1.079. \qquad (6)$$

Figure 7 clearly shows that shear stress undulates in transversal direction. Comparison of this figure with previous figures shows that the bed shear stress is lower than the average values around low streamwise velocity region (e.g., $y/b \approx 0.1, 0.4$ in Figure 7, which corresponds to $y/H \approx 0.7, 2.9$ in Figure 3(a) and (b) and $y/H \approx 0.6, 2.3$ in Figure 3(c) and (d)) and it is higher than the average values around high streamwise velocity region (e.g., $y/b \approx 0.1, 0.4$ in Figure 7, which corresponds to $y/H \approx 0.7, 2.9$ in Figure 3(a) and (b) and $y/H \approx 0.6, 2.3$ in Figure 3(c) and (d)). Undulation of bed shear stress in lateral direction is partially in agreement with the equation of Ikeda [32] and it shows maximum and minimum values nearly in the same location. However, the trend of experimental results is entirely different from the equation of Ardiclioglu et al. [33]. This difference arises from the fact that the equation of Ardiclioglu et al. [33] only considers direct effect of side walls on the bed shear stress without any consideration for periodic undulation due to the secondary currents. Figure 7 also shows that in the case of Type 1 rough bed measurements (Figure 7(a) and (c)), the ratio of maximum local shear stress to the cross-wise average shear stress ($\tau_{\text{maximum}}/\tau_{\text{ave}}$) is around 1.15, while, in Type 1 rough bed measurements (Figure 7(b) and (d)), the ratio of $\tau_{\text{maximum}}/\tau_{\text{ave}}$ is around 1.35. This observation also expresses intensification of the bed shear stress transversal variations in the cases of larger bed roughness elements.

4. Discussion

In this study, three-dimensional structure of turbulent flow in a wide rectangular open channel with rough bed was explored through measurements of the flow field using a micro-ADV and local bed shear stress. More specifically, the effect of roughness elements on flow characteristics variations in the cross-section was explored with respect to the secondary currents formation. Although a large number of studies have considered rectangular open-channel flows [15,27], the importance of bed roughness in lateral variation of flow characteristics has not been marked out properly.

Results of all experiments in the present study showed noticeable lateral variation of flow characteristics. Contour-maps of mean streamwise velocity were composed of regions with low and high values. The lateral spacing between the low mean streamwise velocity regions was almost twice the water depth. Moreover, it was found that in the region of low streamwise velocity, Reynolds shear stress and bed shear stress were high, while in the region with high streamwise velocity, Reynolds shear stress and bed shear stress were low. In previous experimental studies, similar behaviors have been reported due to the presence of secondary currents [12,22,25]. Unfortunately, the quality of vertical and transversal velocity components of our measurements was not high enough to allow direct observation of the secondary currents. However, the observed behaviors could be sufficient to conclude that the lateral variations of flow characteristics resulted from the secondary currents formation.

Secondary currents should be formed in the near side walls region ($y/H < 2.5$). Outside this region, formation of secondary currents requires some reinforcing mechanism, which is generally provided by ridges and troughs of longitudinal sand ribbons [14]. Since rough beds in our experiments were immobile, the rearrangement of bed materials was highly unlikely to produce such longitudinal ridges and troughs. For generation of secondary currents, the flow should have two special features: Firstly, velocity fluctuations should be anisotropic and secondly, turbulent properties of the flow should be heterogeneous [13,22]. It has been observed that bed roughness reduces turbulence anisotropy of near bed flow [34]. Accordingly, in some studies, formation of secondary currents in the central zone of open channel is attributed to the difference between roughness of bed and side walls [12,23]. Indeed, the difference between roughness of bed and side walls strengthens the corner surface vortex, which maintains the cellular pattern throughout the cross-section [23]. In such reasoning, maintenance of the cellular pattern throughout the cross-section is related to the strengthening of the corner surface vortex. On the hand, some other studies have showed that secondary currents formation in the central zone of rough bed channel results from local protrusions of the bed roughness elements. According to this hypothesis, reinforcement of secondary currents is a consequence of persistency in the occurrence of vortex stretching around rough bed elements [35,36]. In the present study, we notified that lateral variations of all flow characteristics were enhanced when the roughness of the channel bed increased. Observation of stronger lateral variation in the presence of larger roughness elements could support the importance of rough elements protrusions in the secondary currents generation. In fact, in the case of large rough bed elements, vortex stretching induced by bed roughness could be enhanced and, consequently, the induced secondary flow was more prominent. It should also be considered that in the case of larger roughness elements, the difference between roughness of bed and side walls was larger; therefore, stronger variation of flow characteristics could be observed by strengthening of the corner surface vortex. However, from Figure 3, it seems that the locations of low and high streamwise velocity regions remain nearly constant for similar rough beds with different aspect ratios. Indeed, although the lateral spacing of low and high streamwise velocity regions was scaled with water depth, there was still slight difference between the values of lateral spacing ($2.2H$ in H13R1 and H13R2 experiments and $1.9H$ in H16R1 and H16R2 experiments). Remember that the lateral spacing of secondary currents cells was estimated just from mean streamwise velocity contour-maps and we did not have trustable contour-maps for vertical and transversal velocity components to control this finding. However, if we accept the observed values as lateral spacing of the secondary currents cells, this observation could show the importance of local roughness elements in formation of secondary currents. Therefore, it can be stated that our observations support the idea that vortex stretching due to local rough elements is important for secondary currents formation. Further studies are needed firstly to observe similar behavior with more details, especially in the vertical and transversal velocity components, and secondly to explain how quasi-cyclic longitudinal strips of low and high values of mean velocity are formed by local vortex stretching around rough bed elements.

Another important point concerning rough bed flow studies is related to the application of double averaging method. In rough bed flow studies, it is common to average time averaged flow characteristics within a thin spatial slab parallel to the bed [20,37,38]. This systematic framework for the study of heterogeneous flows is known as double (or spatially) averaging method [37]. In this framework, information on local variation of flow variables is lost due to the spatial averaging, but some hydraulic concepts such as flow uniformity, two-dimensionality, and bed shear stress are more properly defined. Moreover, spatially averaged viscous drag, form drag, and additional terms due to spatial heterogeneity, known as form induced (or dispersive) stresses, appear explicitly in the double averaged equations [39]. In this way, double averaged flow variables and bed shear stress are coupled consistently with spatially averaged roughness parameters.

A key challenge in double averaging method is attaining good understanding of proper spatial averaging domain to provide spatially representative estimates of the flow [36].

As mentioned above, theoretically spatial averaging must be done within a thin spatial slab parallel to the bed [39]. However, in many studies, for simplicity, only the data in the streamwise direction along the centerline of the channel are spatially averaged [5,7]. In fact, spatial averaging in the streamwise direction along the centerline of the channel is correct if the lateral variation of flow characteristics could be neglected and 2D flow assumption is valid. However, the present study, in line with the previous studies on the wide open channel flows, shows that transversal variations of flow characteristics are not negligible. This fact points out that the spatial averaging among experimental data measured at different streamwise and spanwise locations seems to be a better representative of the near-bed heterogeneous flow. Following this approach, Cooper and Tait [40] applied spatial averaging at 9 different PIV measurement planes in lateral positions across the bed. Using this averaging method, Cooper and Tait [40] properly considered lateral variations of flow characteristics in spatial averaged characteristics. Therefore, in future studies of rough bed flows using double averaging approach, the spatial samples should be selected not only in different locations along channel centerline, but also in points with various streamwise and crosswise locations.

5. Conclusion

Laboratory measurements on a rectangular channel over a rough bed with smooth lateral walls showed consistency with few results reported in the literature. The lateral variations of streamwise velocity, turbulent characteristics, and bed shear stress were well defined. The noticeable variations represented the presence of a cellular structure that was approximately on the same scale with flow depth.

Flow measurements in the presence of larger bed roughness elements showed amplification of the lateral variations of flow characteristics. This observation showed the formation of stronger and clearer secondary currents due to the bed roughness. Strengthening of secondary currents was discussed with regards to two possible mechanisms: 1) stronger vortex stretching near local rough bed due to protrusion of larger rough elements, and 2) strengthening of surface vortex due to higher difference in the roughness of bed and side walls. Despite lack of information on vertical and spanwise components of velocity in the present study, some findings (e.g., fixed location of low and high velocity regions in the experiments with different aspect ratios) suggested that vortex stretching of near rough elements could play an important role in strengthening of the secondary currents. This does not mean that the effects of side walls can be negligible in the central part of the channel. More detailed study of this observation requires analysis of coherent structures in instantaneous flow field. Future studies can examine instantaneous velocity field to properly justify how secondary currents are still present in the area far from side walls in presence of bed roughness elements.

Besides, selection of a suitable domain for implementing spatial averaging in the case of secondary currents formation was discussed. It was suggested to apply spatial averaging not only in streamwise direction, but also in both streamwise and spanwise directions. In this method of averaging, the time averaged values are selected from both low and high velocity regions and the effects of secondary currents are properly considered in the double averaged values.

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