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Effect of Reynolds Number on Wall-normal Turbulence Intensity in a Smooth and Rough Open Channel Using both Outer and Inner Scaling

Md Abdullah Al Faruque, Ram Balachandar

***Abstract*—**Sudden change of bed condition is frequent in open channel flow. Change of bed condition affects the turbulence characteristics in both streamwise and wall-normal direction. Understanding the turbulence intensity in open channel flow is of vital importance to the modeling of sediment transport and resuspension, bed formation, entrainment, and the exchange of energy and momentum. A comprehensive study was carried out to understand the extent of the effect of Reynolds number and bed roughness on different turbulence characteristics in an open channel flow. Four different bed conditions (impervious smooth bed, impervious continuous rough bed, pervious rough sand bed, and impervious distributed roughness) and two different Reynolds numbers were adopted for this cause. The effect of bed roughness on different turbulence characteristics is seen to be prevalent for most of the flow depth. Effect of Reynolds number on different turbulence characteristics is also evident for flow over different bed, but the extent varies on bed condition. Although the same sand grain is used to create the different rough bed conditions, the difference in turbulence characteristics is an indication that specific geometry of the roughness has an influence on turbulence characteristics. Roughness increases the contribution of the extreme turbulent events which produces very large instantaneous Reynolds shear stress and can potentially influence the sediment transport, resuspension of pollutant from bed and alter the nutrient composition, which eventually affect the sustainability of benthic organisms.

***Keywords*—**Open channel flow, Reynolds Number, roughness, turbulence.

I. INTRODUCTION

OPEN channel flow comprises a shear/boundary layer like flow and it is of vital importance to understand its structure and dynamics. Researchers have added interest in entrainment and the exchange of energy and momentum to the modelling of sediment transport, resuspension and bed formation. The shape, size, and arrangement of bed particle could contribute to the modulation of turbulence in one way or other. Flow over rough surface has significant importance in industrial applications. However, as rightly pointed by [1], flow over rough surface continues to be Achilles heel of turbulence research. The suggested use of turbulent boundary layer data for modeling open channel flow is questionable due to basic differences between the two, influenced by the channel aspect ratio and the presence of the free surface. The flow in an open channel consists of a free surface and side walls that cause the formation and enhancement of secondary currents. The wall-normal velocity fluctuations were also dampened by the free surface of the open channel. Reference [2] studied the flow progression from developing to fully developed flow. They studied the flow development across the fully developed flow section and found that shear velocity gradually decreases toward the sidewall but varies in an oscillatory manner across the flow section for b/h = 2 and 3. Here, b is the width of channel, and h is the depth of flow. They noted that at the axis of a fully developed turbulent flow section the boundary layer extends to the water surface if the aspect ratio $b/h \geq 3$. They also noted that the wake effect on the boundary layer velocity profiles is weak in the developing boundary flow but becomes important in the velocity profiles of the fully developed boundary layers. They did not observe any velocity dip for channel centerline even for channel with aspect ratio as low as b/h = 3. Reference [3] reported turbulence statistics in a fully developed, open-channel flow above a uniformly distributed packed bed of non-erodible, uniform-diameter glass spheres. They noted that for locations above the roughness sublayer, the distributions of the second-order turbulent stresses are similar to the smooth-wall distributions when the stresses are non-dimensionalized by friction velocity. Reference [4] investigated the motion of solid particles near the wall in a turbulent boundary layer in a water flume and noted that coherent wall structures are the dominant factor affecting particles motion near a solid boundary in turbulent flow, as well as deposition and entrainment. Reference [5] performed experiments to measure the characteristics of a turbulent boundary layer developing on a rough surface placed in an open channel flow at close proximity to the free surface. They redefined the boundary layer by the turbulence profile and at a depth of constant turbulence intensity. Reference [6] investigated the effects of surface roughness on the transport and mixing properties in turbulent boundary layers created in an open channel flow. They noted that surface roughness significantly enhances the levels of the Reynolds stresses, turbulence kinetic energy, and turbulence diffusion in a way that depends on the specific geometry of the roughness elements. Laser Doppler anemometer (LDA) was used by [7] to measure the velocity on a smooth open channel flow with two geometrically

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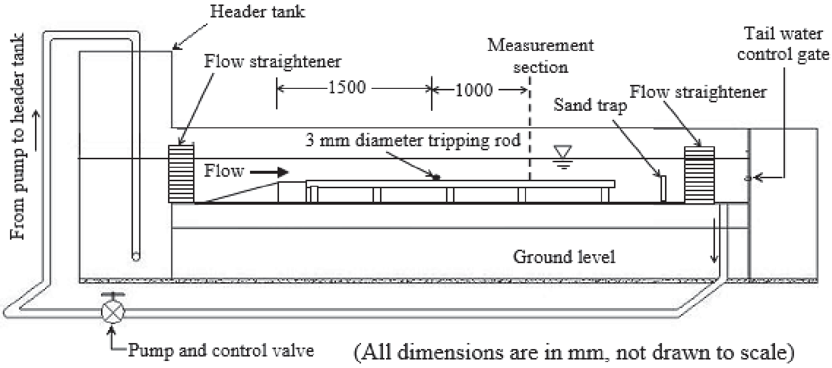
different types of rough surfaces. Although the free surface influenced the boundary layer in an open channel flow, [7] found similarity in the roughness effects on the velocity field compared to those observed in a zero-pressure gradient turbulent boundary layer. Reference [7] also observed substantial increment of the value of wake parameter due to the surface roughness in comparison to the value of the same but the flow over smooth wall. They noted that roughness enhances the levels of the turbulence intensities and Reynolds shear stress over most of the boundary layer, and promotes isotropy. They also noted that triple correlations and turbulence diffusion were strongly modified by surface roughness. Reference [8] pointed out the importance of buffer layer (sandwiched between viscous layer and log-law layer) in turbulence research, because of its critical role in the turbulent bursting phenomena. The formation of secondary current due to the effect of side wall was related to the aspect ratio (width/depth ratio of flow, b/h) by [8], and [8] had noted that on the centerline of the flume and for b/h<5, the maximum velocity occurred below the free surface (velocity dip phenomenon). Reference [8] also proposed the classification of the rectangular channels based on the examination of the critical value of b/h as narrow open channel if $b/h<(b/h)_{crit}$ or wide open channel if $b/h > (b/h)_{crit}$, with setting $(b/h)_{crit} = 5$ for smooth channel. Reference [9] examined the effect of surface roughness on the higher-order velocity moments in a turbulent open channel flow. Their results showed that the triple products are sensitive to the wall condition and the effects are prevalent throughout the depth of flow. Reference [10] studied the effect of Reynolds number on the velocity characteristics of smooth open-channel flows with and without perturbation. They observed that the turbulence intensity and Reynolds shear stress profiles exhibited Re dependence, irrespective of the scaling used. It should be noted from above discussion that the effects of surface roughness on turbulence are not conclusive. There are conflicting opinions among researchers about the extent of effect of bed roughness and also about the effect of Reynolds number on turbulence intensity.

II. EXPERIMENTAL SETUP

An 8-m long rectangular open channel flume (cross-section 1100 mm x 920 mm) to carry out the experiments. Fig. 1 shows the schematic of the open channel flume and experimental setup used in this study. The size of the header tank upstream of the rectangular cross-section was 1.2 m square and 3.0 m deep. The normal flow depth was 100-mm, resulting in a width-to-depth ratio (b/h) of approximately 11. The corresponding aspect ratio (width-to-depth ratio) of 11 considered being large enough to minimize the effect of secondary currents and the flow can be considered to be nominally two-dimensional. Two 15-horsepower centrifugal pump units were used to recirculate the water. Transparent tempered glass was utilised in the sidewalls and bottom of the flume to facilitate velocity measurements using a LDA. The flume is a permanent facility and the quality of flow has been confirmed in several previous studies. The bottom slope of the flume was adjustable and for this study, it was kept horizontal. The discharges (recirculating flow) were kept constant to 720 GPM and 450 GPM for these series of tests.

The authors were used four different types of bed surface conditions in this study. An aluminum plate spanning the entire width of flume (Fig. 2 (a)) was used to generate the hydraulically smooth surface and considered it as the base case. Also studied were three different types of rough surfaces. Sand particles with characteristics shown in Table I were used to create the rough surfaces. As shown in the Table I, the sand can be considered as uniform with median grain diameter of 2.46-mm. To generate the first rough surface which was designated to be distributed roughness on impervious surface, 18-mm wide sand strips alternated with 18-mm wide smooth strips were glued with smooth aluminum plate as shown in Fig. 2 (b). Second roughness condition consisted of same sand grain glued over the entire smooth surface as shown in Fig. 2 (c). 3.7 m long uniform sand bed as shown in Fig. 3 was used as the third rough surface and was generated by using 200-mm thick natural sand. The flow conditions during the test were maintained in such a way that the sand movement was not initiated. However, a sand trap was provided at the downstream of the bed to prevent any accidental transport of sand particles into the pump/piping assembly.



(All dimensions are in mm, not drawn to scale)

Fig. 1 Schematic of the open channel flume and experimental setup

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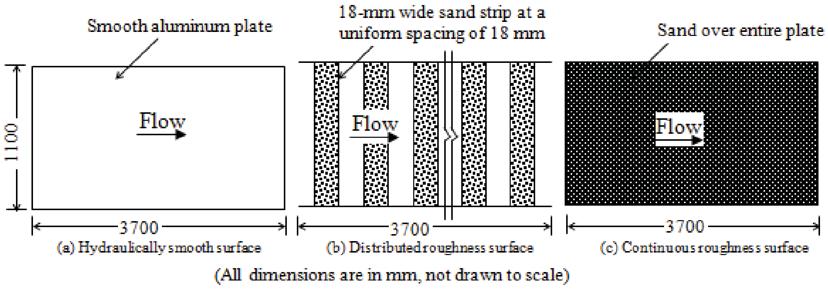

Fig. 2 Plan view of different fixed bed condition

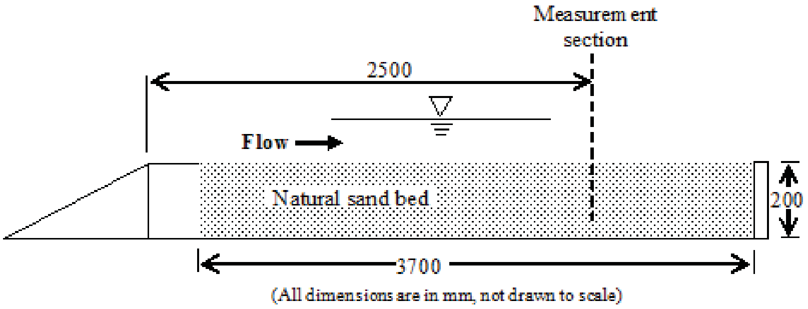

Fig. 3 Section of natural sand bed

TABLE I
GRADATION MEASUREMENTS OF THE SAND

d_{50} (mm)	2.46
d_{95}/d_5	1.91
d_{95}/d_{50}	1.34
d_{84}/d_{50}	1.26
$\sigma_g = \sqrt{d_{84}/d_{16}}$	1.24
$C_z = d_{30}^2/(d_{60}d_{10})$	1.00

Two different Reynolds numbers were used for each test condition. Reynolds numbers were chosen in order to keep flow condition as sub-critical (i.e. Froude numbers less than unity) [11]. Flow conditions corresponded to values of the Reynolds number are $Re_h = U_{avg}d/\nu \approx 47{,}500$ & 31,000 and corresponded to Froude number are $F_r = U_{avg}/(gd)^{0.5} \approx 0.40$ & 0.24 [11]. Here, U_{avg} is the average velocity, d is the depth of flow, g is the acceleration due to gravity, and ν is the kinematic viscosity of the fluid. Measured variation of water surface elevation was less than 1 mm over a streamwise distance of 600 mm implying a negligible pressure gradient [11]. Flow straighteners were used at the beginning and the end of flume to condition the flow. To ensure a turbulent boundary layer, a trip was located 1.5 m downstream of smooth bed and spanned the width of the flume. The trip was made of 3 mm diameter rod glued to the bottom of smooth plate. The measurements over smooth plate were obtained 1 m downstream of the trip. The measurements for the distributed roughness were conducted on top of 60th sand strip [11]. All the measurements were conducted along the centerline of the channel to minimize secondary flow effects. Preliminary tests were conducted to ensure a fully developed flow condition. The summary of the test conditions was presented in Table II [11].

TABLE II
SUMMARY OF THE TEST CONDITIONS

Test	Bed Condition	U_{avg} (m/s)	d (mm)	R_{eh}	F_r
1	Smooth bed	0.375	~ 100	~ 47500	~ 0.40
2		0.24	~ 100	~ 31000	~ 0.24
3	Distributed roughness	0.357	~ 100	~ 47500	~ 0.40
4		0.24	~ 100	~ 31000	~ 0.24
5	Continuous roughness	0.358	~ 100	~ 47500	~ 0.40
6		0.23	~ 100	~ 31000	~ 0.24
7	Natural sand bed	0.40	~ 100	~ 47500	~ 0.40
8		0.25	~ 100	~ 31000	~ 0.24

The instantaneous velocities were measured by a two-component commercial fibre-optic LDA of Dantec Inc. powered by a 300-mW Argon-Ion. Several previous studies had been used this system and details are avoided here for brevity. The optical elements include a Bragg cell, a 500-mm focusing lens and the beam spacing was 38 mm. 10,000 validated samples were acquired at each measurement location. Prior to the measurement of each set of data, the side wall of the flume was cleaned to minimize extraneous light scattered from particles distributed throughout the illuminating beams. The configuration of the present two-component LDA system could not permit measurements very close to the wall, while one-component (streamwise velocity) measurements were made over the entire depth. The LDA probe was tilted at 2° towards the bottom wall to capture near wall data for two-component velocity measurements. References [4], [12] had tilted the probe to 3° and 2°, respectively, from the horizontal to allow data acquisition closer to the wall.

III. RESULTS

Fig. 4 shows the variation of wall-normal turbulence intensity with outer scaling on the smooth and the rough bed surfaces for the two Reynolds numbers. Depth of flow and maximum velocity are the two directly measured quantities and are used as the length and velocity scales, respectively. Any additional uncertainties related to scaling parameters with computed quantities would reduce by using the directly measured quantities. One can easily see from Fig. 4 (a) that wall-normal turbulence intensity attains a maximum value very close to the wall for both Reynolds numbers. The effect of Reynolds number is very evident throughout the flow depth with lower Reynolds number shows higher wall-normal turbulence intensity except the location nearest to the bed. Figs. 4 (c) and (d) show the wall-normal turbulence intensity for flow over distributed roughness bed and continuous roughness bed respectively. The effect of Reynolds number is only evident for the distance ≈0.20d from the bed for flow over distributed roughness bed and continuous roughness bed. Fig. 4 (b) shows the wall-normal turbulence intensity for flow over natural sand bed and there is almost no evidence of effect of Reynolds number. Effect of Reynolds number for flow over different bed varies but the magnitude of wall-normal turbulence intensity is always much higher for flow over rough beds compare to the flow over smooth bed. Closer to the free surface, the results indicate that wall-normal turbulence attains a nearly constant value, except for the case of bed surface with distributed roughness. The location of attainment of constant wall-normal turbulence intensity is different for different surface conditions. The distance from bed to the start of the constant wall-normal turbulence intensity is 0.5d for smooth bed surface condition followed by continuous roughness and sand bed (~0.62d). Although the same sand grain is used to create the three different rough bed conditions, the difference in turbulence intensity is an indication that specific geometry of the roughness has an influence on turbulence structure.

In order to understand the effect of scaling on the variation of wall-normal turbulence intensity, the same figure (Fig. 4) is now plotted in Fig. 5 to show the variation of the wall-normal turbulence intensity with inner scaling on the smooth and the rough bed surfaces for the two Reynolds numbers. Directly measured quantity like depth of flow and calculated quantity like friction velocity (U_τ) are used as the length and velocity ($v^+ = v/U_\tau$) scales, respectively. One can note there are not much difference on the effect of Reynolds number for the flow over smooth (Fig. 5 (a)) and sand bed (Fig. 5 (b)) but there is an obvious difference in the trend for the flow over distributed roughness bed (Fig. 5 (c)) and continuous roughness bed (Fig. 5 (d)) with higher Reynolds number shows higher wall-normal turbulence intensity. The effect of Reynolds number is evident for the distance ≈0.45d from the bed for flow over distributed roughness bed and continuous roughness bed. One can also note that the magnitude of wall-normal turbulence intensity shows minimal effect of bed roughness in case of inner scaling. Both scales show similar trend of the variation of wall-normal turbulence intensity for the location closer to the free surface.

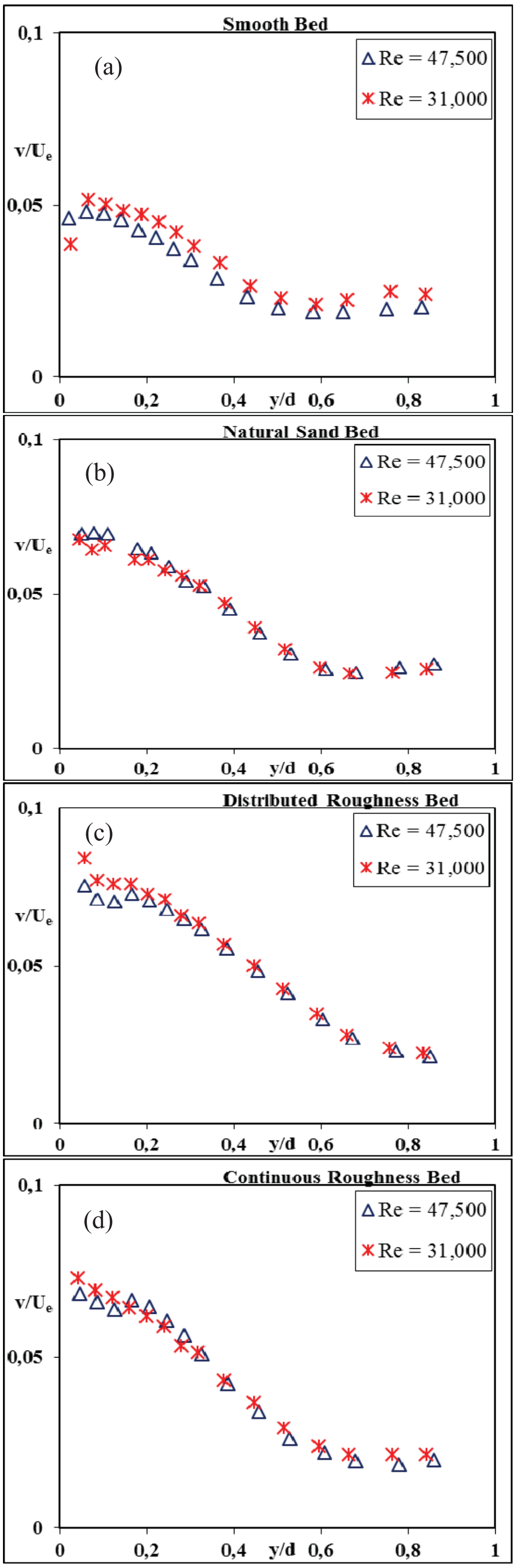

Fig. 4 Vertical turbulence intensity in outer scaling for two different Reynolds number and for flow over different bed conditions

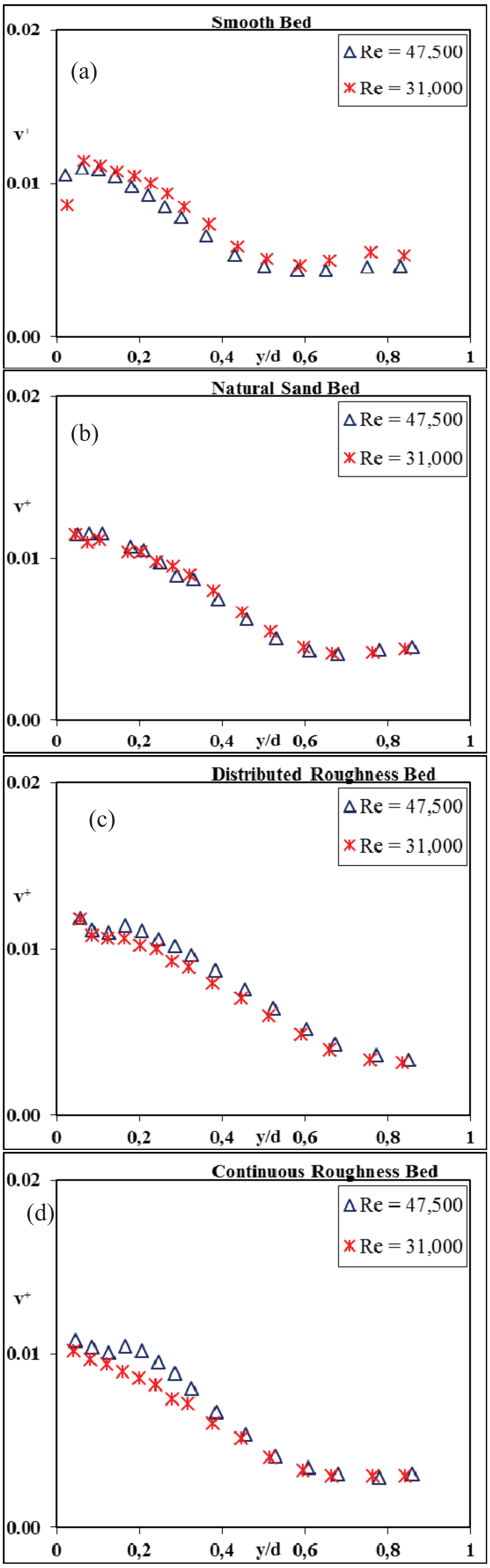

Fig. 5 Vertical turbulence intensity in inner scaling for two different Reynolds numbers and for flow over different bed conditions

IV. CONCLUSION

The present study was carried out to understand the extent of effect of roughness and Reynolds number on wall-normal turbulence intensity in open channel flow by using both outer and inner scaling. To this end, two different Reynolds numbers and four different types of bed surface conditions were adopted in the study. The main findings are summarized as follows:

1. The effect of Reynolds number on wall-normal turbulence intensity is distinctly visible for most of the depth for flow over smooth bed irrespective of scaling used.
2. There is no effect of Reynolds number on wall-normal turbulence intensity for flow over natural sand bed irrespective of scaling used.
3. The effect of Reynolds number on wall-normal turbulence intensity is only visible for near bed for flow over distributed roughness and continuous roughness beds. The depth of flow affected is dependent on the scaling used to normalize the wall-normal turbulence intensity.
4. Turbulence characteristics are found to be different for different rough surfaces made up from the same sand grain, which is a clear indication that geometric pattern of the roughness has an influence on turbulence structure.
5. One can see the wall-normal turbulence intensity propagates from the stream bed to throughout the flow depth indicating a two-dimensional flow condition.
6. The presence of the wall-normal turbulence intensity would change the mixing characteristics of the flow.
7. The wall-normal turbulence intensity coupled with the streamwise turbulence intensity would produce Reynolds shear stress throughout the flow depth. The Reynolds shear stress at near bed location can have a great impact on bed stability.
8. The effect of Reynolds number on wall-normal turbulence intensity reduces with the introduction of roughness except the immediate vicinity of the bed.

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