International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:9, No:12, 2015

Variation of Streamwise and Vertical Turbulence Intensity in a Smooth and Rough Bed Open Channel Flow

Md Abdullah Al Faruque, Ram Balachandar

***Abstract*—**An experimental study with four different types of bed conditions was carried out to understand the effect of roughness in open channel flow at two different Reynolds numbers. The bed conditions include a smooth surface and three different roughness conditions, which were generated using sand grains with a median diameter of 2.46 mm. The three rough conditions include a surface with distributed roughness, a surface with continuously distributed roughness and a sand bed with a permeable interface. A commercial two-component fibre-optic LDA system was used to conduct the velocity measurements. The variables of interest include the mean velocity, turbulence intensity, correlation between the streamwise and the wall normal turbulence, Reynolds shear stress and velocity triple products. Quadrant decomposition was used to extract the magnitude of the Reynolds shear stress of the turbulent bursting events. The effect of roughness was evident throughout the flow depth. The results show that distributed roughness has the greatest roughness effect followed by the sand bed and the continuous roughness. Compared to the smooth bed, the streamwise turbulence intensity reduces but the vertical turbulence intensity increases at a location very close to the bed due to the introduction of roughness. Although the same sand grain is used to create the three different rough bed conditions, the difference in the turbulence intensity is an indication that the specific geometry of the roughness has an influence on turbulence structure.

***Keywords*—**Open channel flow, smooth bed, rough bed, Reynolds number, turbulence.

I. INTRODUCTION

CERTAIN unique features in open channel flow (OCF) stemming from the presence of a free surface and river beds that are movable and often strongly irregular do not render an easy analysis. Sudden change of bed surface is often encountered in hydraulic engineering and the change of bed roughness changed the velocity distribution and turbulent characteristics in both streamwise and wall-normal direction. Numerous hard metals were deposited into river bed due to uncontrolled waste disposal into stream and channels. During the movement of marine transport, the hard metal deposited in the river bed can stir up and flow to a new location and cause destruction of fisheries resources. Reference [1] studied the flow progression from a developing state to a fully developed condition and noted that along the axis of a fully developed section, the boundary layer extends to the water surface if the aspect ratio $b/d \geq 3$. Near the free surface, they did not observe any dip in the velocity profile at the channel centerline even for channel with aspect ratio as low as $b/d = 3$. Reference [2] related the aspect ratio (width/depth ratio of flow, b/d) to the formation of secondary currents and noted that the maximum velocity on the centerline occurred below the free surface for $b/d < 5$ (velocity-dip phenomenon).

II. EXPERIMENTAL SETUP

Experiments were carried out in a 9-m long rectangular open channel flume (cross-section 1100 mm x 920 mm). A schematic drawing of the open channel flume and experimental setup used in this study is shown in Fig. 1. The sidewalls and bottom of the flume are made of transparent tempered glass to facilitate velocity measurements using a laser Doppler anemometer. The flume is a permanent facility and the quality of flow has been confirmed in previous studies. The channel bottom slope is adjustable. For the present experiments, the channel bottom was set to be horizontal. A summary and details of test conditions can be found in [3] and avoided here for brevity. The header tank upstream of the rectangular cross-section was 1.2 m square and 3.0 m deep. The nominal flow depth (d) in the measurement region was 100 mm, resulting in a width-to-depth ratio (b/d) of approximately 11. This value of the aspect ratio is considered large enough to minimize the effect of secondary currents and the flow can be considered to be nominally two-dimensional [2]. Flow straightners were used at the beginning and the end of flume to condition the flow. The flow conditions were maintained in such a manner that there was no initiation of sand movement. 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.

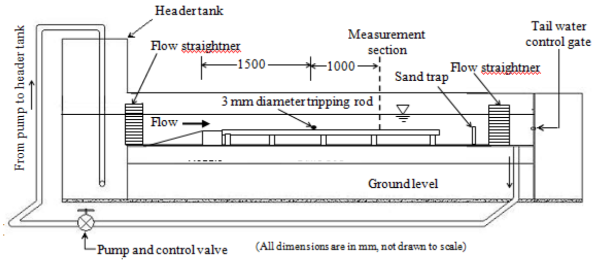
Four different types of bed surface conditions were used in this study. The base case was a hydraulically smooth surface generated using a 3.7 m long polished aluminum plate spanning the entire width of flume (Fig. 2 (a)). Three different types of rough surfaces were used. Sand particles ($d_{50} = 2.46$ mm, $\sigma_g = \sqrt{d_{84}/d_{16}} = 1.24$) were used to create the rough surfaces. To generate the first rough surface (designated as 'distributed roughness'), 18-mm wide sand strips were glued to the smooth aluminium plate alternating with 18-mm wide

---

Md Abdullah Al Faruque, Associate Professor is with the Civil Engineering Technology, Rochester Institute of Technology, 78 Lomb Memorial Drive, Rochester, NY 14623 USA (Corresponding author, phone: 1-585-475-6664; fax: 1-585-475-7964; e-mail: aafite@rit.edu).

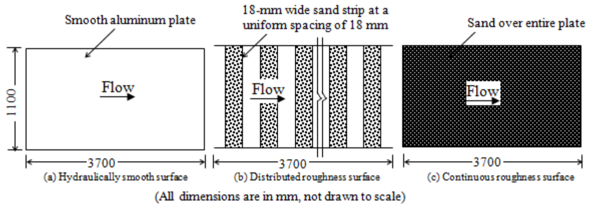
Ram Balachandar is with the Associate Vice Provost and Executive Director, Centre for Executive and Professional Education, Professor, Faculty of Engineering, University of Windsor, 401 Sunset Ave., Windsor, ON Canada N9B 3P4 (e-mail: rambala@uwindsor.ca).

smooth strips as shown in Fig. 2 (b). The second roughness condition consisted of the same sand grains glued over the entire smooth surface as shown in Fig. 2 (c) (continuous roughness). In both cases, the sand was affixed to the aluminum plate in a single grain layer. Third rough surface was generated using 200-mm thick and 3.7 m long uniform sand bed as shown in Fig. 3.



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

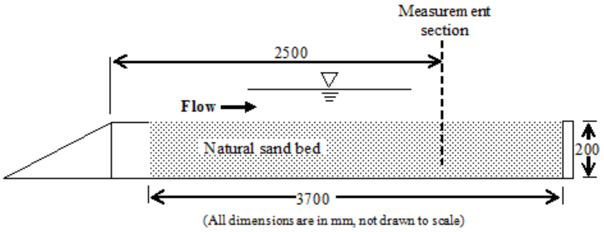
Fig. 1 Schematic of the open channel flume and experimental setup



(a) Hydraulically smooth surface (b) Distributed roughness surface (c) Continuous roughness surface

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

Fig. 2 Plan view of different fixed bed condition



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

Fig. 3 Section of natural sand bed

To ensure the presence of a turbulent boundary layer, a 3-mm diameter rod was used as a trip upstream of the measurement region. The boundary layer shape factor for the smooth bed, which can be defined as the ratio of displacement to momentum thickness is found to be ≈ 1.3, which is an indication of fully developed turbulent flow [4]. The measurements for the distributed roughness were conducted on top of 60th sand strip. 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.

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). Flow conditions corresponded to values of the Reynolds number are $Re_h = U_m h/\nu \approx 55{,}000$ & 35,000 and corresponded to Froude number are $F_r = U_m/(gh)^{0.5} \approx 0.43$ & 0.27. Here, U_m is the maximum velocity, h 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. Flow straighteners were used at the beginning and the end of flume to condition the flow. The summary of the test conditions were presented in Table I.

TABLE I
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

III. RESULTS

Fig. 4 shows the streamwise turbulence intensity on the smooth and the rough bed surfaces in outer variables for the lower Reynolds number. Directly measured quantities like depth of flow and maximum velocity are used as the length and velocity scales, respectively, to reduce any additional uncertainties related to scaling parameters with computed quantities. One can note from Fig. 4 that streamwise turbulence intensity attains a maximum value very close to the wall for all bed surface conditions. Smooth wall shows the highest turbulence intensity at locations very close to the bed. Among the rough beds, the flow over distributed roughness shows the highest peak at y/d ~ 0.08 followed by continuous roughness and natural sand bed at y/d ~ 0.04. At larger values of y/d, the streamwise turbulence intensity reduces towards the free surface. With the initial significant drop of streamwise turbulence intensity for smooth bed surface condition, the reduction of streamwise turbulence intensity is linear for all surface conditions. Closer to the free surface, the results indicate that streamwise turbulence attains a nearly constant value. The location of attainment of constant streamwise turbulence intensity is different for different surface conditions. The distance from bed to the start of the constant streamwise turbulence intensity is 0.5d for smooth bed surface condition, ~ 0.62d for continuous roughness and sand bed and 0.75d for distributed roughness. Although the distance from bed to attain a constant value of streamwise turbulence intensity is the same for the continuous roughness and sand bed, the value of streamwise turbulence intensity is found to be marginally higher for sand bed condition. With the exception of the region very close to the bed, roughness effect is prevalent throughout the flow depth with distributed roughness showing a maximum deviation from a smooth bed followed by sand bed and continuous roughness. 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. The variation of streamwise turbulence intensity for higher Reynolds number flow [3] shows similar trend to the lower Reynolds number flow. However, the flow over distributed roughness shows less deviation at the higher Reynolds number. In addition, differences between sand bed and continuous roughness bed are much higher for flow at the higher Reynolds number.

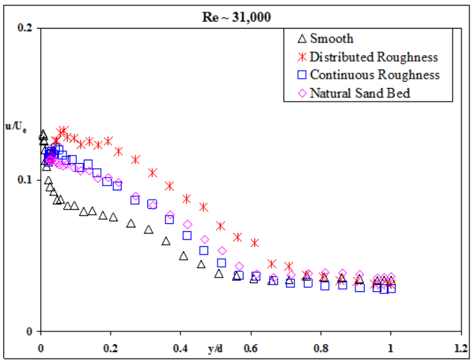


Fig. 4 Streamwise turbulence intensity for flow over different bed condition

Fig. 5 shows the vertical turbulence intensity on the smooth and the rough bed surfaces in outer variables for the lower Reynolds number. One can note from Fig. 4 that distributed roughness shows the highest turbulence intensity at locations very close to the bed followed by the continuous roughness, sand bed and smooth bed. At larger values of y/d, the vertical turbulence intensity reduces towards the free surface. The reduction of vertical turbulence intensity is linear for all surface conditions. Closer to the free surface, the results indicate that vertical turbulence attains a nearly constant value. The location of attainment of constant vertical turbulence intensity is different for different surface conditions. The distance from bed to the start of the constant vertical turbulence intensity is 0.5d for smooth bed surface condition, ~ 0.65d for continuous roughness and sand bed and 0.75d for distributed roughness. With the exception of the region very close to the bed, roughness effect is prevalent throughout the flow depth with distributed roughness showing a maximum deviation from a smooth bed followed by very similar value for sand bed and continuous roughness. Again, the difference in turbulence intensity is an indication that specific geometry of the roughness has an influence on turbulence structure. The variation of vertical turbulence intensity for higher Reynolds number flow [3] shows similar trend to the lower Reynolds number flow. However, the flow over sand bed roughness shows higher vertical turbulence intensity comparing with continuous roughness near the free surface.

Describing F_{kv} as vertical flux of the turbulent kinetic energy, Fig. 6 shows the variation of F_{kv} on smooth and rough surfaces in outer variables for the lower Reynolds number. Vertical flux of the turbulent kinetic energy is normally measured as $0.5\left(\overline{v^3}+\overline{vu^2}\right)$ for a two-dimensional flow [7]. Due to the unavailability of the third component of turbulent intensity, an approximate method is adopted here by replacing the coefficient 0.5 with 0.75 [8]. One can note from Fig. 6 that there is a significant change in profile due to roughness and this is an indication that roughness has a significant effect on the transport of the turbulent kinetic energy in the vertical direction. The profiles of F_{kv} for rough beds are displaced higher from the smooth bed through most of the depth. It should be noted that for large-bottomed roughness, [7] did not find any difference in profiles for F_{kv} over the depth between flow between rough and smooth beds.

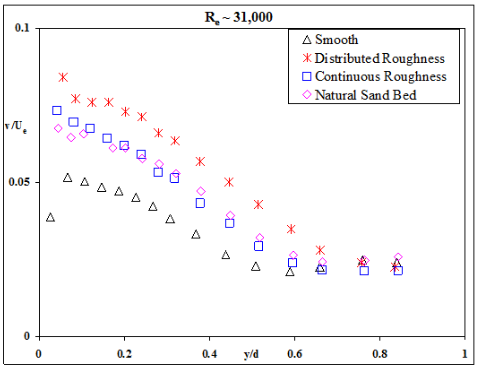


Fig. 5 Vertical turbulence intensity for flow over different bed condition

Reference [9] noted that the location of the outer (larger) peak of F_{kv} is closer to the wall (albeit slightly) as the roughness effect increases. Reference [7] also noted the occurrence of a maximum value near the bed for rib roughness. One can note double peaks from Fig. 6 as first peak at very close to the bed with second peak at a distance of y/d ~ 0.3 from the bed. Although there is an obvious effect of roughness on the peak value of F_{kv}, the location of second peak value (y/d ~ 0.3) is nearly the same for all roughness. The gradient of F_{kv} is the indication of loss or gain of turbulent kinetic energy due to turbulent diffusion. The differences in magnitude of F_{kv} between smooth and rough bed is an indication of the differences in the strength in transport of turbulent kinetic energy between smooth and rough bed. The vertical flux of turbulent kinetic energy gradually reduces after attaining their peak at around y ~ 0.3d and eventually approaches zero near the free surface. The vertical flux of turbulent kinetic energy reaches zero for smooth surface first followed by different roughness. One can also note that the variation of F_{kv} is more or less same for higher Reynolds number flow [3].

Correlation coefficient of the Reynolds stress indicates the degree of similarity of turbulence and could be defined as $\left(R=\frac{-\overline{uv}}{u*v}\right)$. Here, u and v is the turbulence intensity in streamwise direction and normal to the bed, respectively. Reference [2] noted that the value of R increases monotonously with y/h in the wall region, decreases in the free-surface region and remains nearly constant, at about 0.4~0.5, in the intermediate region ($0.1 \leq y/d \leq 0.6$). He also noted that the distribution of R is universal, i.e., it is independent of the properties of mean flow and the wall roughness. One can note from Fig. 7 that the profiles tend to be flatter from the bed up to y/d = 0.3 and is particularly dependent on roughness for the outer region of the flow (y > 0.3d). Variation of R in the outer region with respect to the near-wall, is an indication of change of flow structures between near-wall and outer region, clearly opposing the observation of [2], [10], [9]. One can also note that the variation of R is more or less same for higher Reynolds number flow [3].

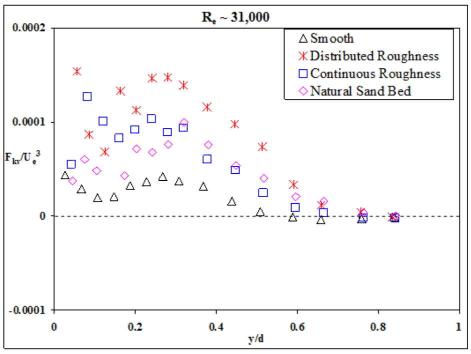


Fig. 6 Distribution of vertical flux of the turbulent kinetic energy for flow over different bed condition

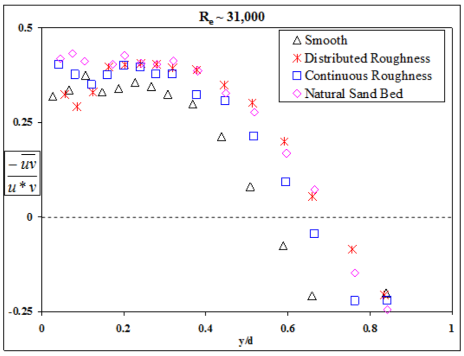


Fig. 7 Distribution of correlation coefficient for flow over different bed condition

IV. CONCLUSION

The present study was carried out to understand the extent of effect of roughness and Reynolds number on streamwise and vertical turbulence. To this end, four different types of bed surface conditions and two different Reynolds number were adopted in the study. The present experimental results disputed the 'wall similarity hypothesis' initially proposed by [5] and generalized by [6], where it was suggested that outside the roughness layer, the turbulent mixing properties in smooth and rough walls should be essentially the same. The main findings are summarized as follows:

1. The effect of the roughness is very much evident throughout the flow depth with the distributed roughness exhibiting the largest deviation from the smooth profile.
2. With the exception of the region very close to the bed, roughness effect on streamwise turbulence intensity is present throughout the flow depth with distributed roughness profile showing a maximum deviation from a smooth bed, followed by sand bed and continuous roughness.
3. Streamwise turbulence intensity reduces but vertical turbulence intensity increases at locations very close to the bed due to the introduction of roughness.
4. 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.
5. The variation of streamwise turbulence intensity for higher Reynolds number flow shows similar trend to the lower Reynolds number flow. However, the flow over distributed roughness shows less deviation at the higher Reynolds number. In addition, differences between sand bed and continuous roughness bed are much higher for flow at the higher Reynolds number.
6. The variation of vertical turbulence intensity for higher Reynolds number flow shows similar trend to the lower Reynolds number flow. However, the flow over sand bed roughness shows higher vertical turbulence intensity comparing with continuous roughness near the free surface.
7. The differences in magnitude of F_{kv} between smooth and rough bed is an indication that roughness has a significant effect on the transport of turbulent kinetic energy in the vertical direction.
8. Variation of the correlation coefficient, R in the outer layer compared to the near-wall is an indication of change of flow structures between the two regions, clearly opposing the observation of [10] that the distribution of R is universal and independent of the properties of the mean flow and the wall roughness.

REFERENCES

[1] Kirkgöz, M. S., and Ardiçhoğlu, M. (1997). "Velocity profiles of developing and developed open channel flow." *Journal of Hydraulic Engineering,* 123(2), 1099-1105.

[2] Nezu, I. (2005). "Open-channel flow turbulence and its research prospect in the 21st century." *Journal of Hydraulic Engineering,* 131(4), 229-246.

[3] Faruque, M. A. A. (2009). "Smooth and rough wall open channel flow including effects of seepage and ice cover." PhD thesis, University of Windsor, Windsor, ON, Canada.

[4] Schlichting, H. (1979). *Boundary-Layer theory*. McGraw-Hill Classic Textbook Reissue Series, McGraw-Hill, Inc., United States of America.

[5] Townsend, A. A. (1976). "The structure of turbulent shear flow." *Cambridge University Press*.

[6] Raupach, M. R., Antonia, R. A., Rajagopalan, S. (1991). "Rough wall turbulent boundary layers." *Applied Mechanics Review,* 44 (1), 1.

[7] Balachandar, R., and Bhuiyan, F. (2007). "Higher-order moments of velocity fluctuations in an open channel flow with large bottom roughness." *Journal of Hydraulic Engineering,* 133(1), 77-87.

[8] Krogstad, P-A., and Antonia, R. (1999). "Surface roughness effects in turbulent boundary layers." *JExperiments in Fluids,* 27, 450-460.

[9] Tachie, M. F. (2001). "Open-channel turbulent boundary layers and wall jets on rough surfaces." PhD thesis, University of Saskatchewan, Saskatchewan, Canada.

[10] Nezu, I. and Nakagawa, H. (1993). *Turbulence in open-channel flows*. IAHR Monograph, A. A. Balkema, The Netherlands.