

Turbulence Characteristics of Flow over Smooth and Rough Beds

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ABSTRACT

Experimental study on turbulence measurements in an open channel with smooth and rough beds using acoustic doppler velocimeter (ADV) has been carried out in the present study. Measured velocity distribution along the depth on smooth and rough beds for different discharges and bed slopes is in good agreement with logarithmic law. The turbulence intensities were more near the bed and less near the water surface. Existing equations for turbulence intensities over-predict the turbulence intensities; thus, new equations are proposed in this study to predict the turbulence intensities. Turbulent kinetic energy decreases from bed to the water surface. Existing equations for distribution of kinetic energy along depth over-predict the turbulent kinetic energy; therefore, new equations are proposed to predict the turbulent kinetic energy for flow on rough and smooth beds.

Keywords: Open channel, velocity distribution, turbulence, rough bed, smooth bed, ADV

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1. INTRODUCTION

Turbulence can be defined as spatially and temporally varying phenomenon in the flow. The main characteristic of turbulence is transfer of momentum in fluid layers by lump of fluid mass called as eddies [1–3]. Several experimental studies have been conducted for the measurement of turbulence using LDA, PIV, ADV, etc., e.g., Blinco and Partheniades [4], Grass [5], Nezu and Rodi [6], Kirkoç [7], Steffler et al. [8], Goring and Nikora [9], etc. Grass [5] found that logarithmic velocity distribution is valid for both smooth and rough bed and inferred that in the presence of roughness, the longitudinal component of turbulence decreases in vertical direction. He defined the bursting phenomenon consisting of inrush and ejection phases on both smooth and rough bed which positively contribute in Reynolds stress generation. Nezu and Rodi [6] measured velocity in open channel flow by the LDA and proposed formula for the distribution

of turbulent intensities along the depth for smooth bed, i.e.,

$$\begin{aligned}u'/u_* &= 2.26 \exp(-0.88y/h) \\v'/u_* &= 1.27 \exp(-0.67y/h) \\w'/u_* &= 1.63 \exp(-y/h)\end{aligned}\quad (1)$$

Where u' , v' and w' are root mean squared turbulent intensity in longitudinal x , lateral y , and vertical z ; h is depth of flow; y is distance along depth from bed; u_* is shear velocity. They also conferred that Reynolds stress ($-\rho \overline{u'w'}$) decreases from bed to water surface. Nezu and Rodi [6] found that eddy viscosity is distributed parabolically along the depth and attains its maxima at the mid-depth.

Wang et al. [10] studied the effect of roughness on turbulent intensities. For uniform gravel bed, if $h/k_s < 1.0$, the u'/u_* was found to be uniform which signifies that roughness affects the whole depth (k_s = average roughness height). For $h/k_s \geq 1.36$, the u'/u_* was found to approach the smooth bed result

of Nezu and Rodi [6] gradually. When h/k_s varies in the range of 1.36–3.31, the value of u'/u_* was constant for a given roughness and as the roughness was increased the value of constant also increased substantially. For $h/k_s > 3.31$, u'/u_* was found to follow Nezu and Rodi [6] in a more precise manner, but Nezu's constant was found to be a function of h/k_s . For $h/k_s \geq 4.0$, Nezu's constant became independent of roughness size and gave following formulation for turbulent intensity distribution along the flow depth:

$$u'/u_* = 2.14 \exp(-0.8y/h) \quad (2)$$

The maximum value of u'/u_* was in the range of 1.8–2.0 much lesser than literature-quoted range of 2.6–3.4. Turbulent intensities at the non-uniform rough bed were also found to approach the Nezu and Rodi [6] equation. For rough bed, Goring and Nikora [9] gave the following equations for the computation of turbulent intensities and turbulent kinetic

$$\left(\frac{u'}{u_*}\right)^2 = 1.90 - 1.32 \ln\left(\frac{y}{h}\right) \quad (3)$$

$$\left(\frac{v'}{u_*}\right)^2 = 1.19 - 0.49 \ln\left(\frac{y}{h}\right) \quad (4)$$

$$\left(\frac{w'}{u_*}\right)^2 = 0.59 - 0.22 \ln\left(\frac{y}{h}\right) \quad (5)$$

$$\frac{k}{u_*^2} = 1.84 - 1.02 \ln\left(\frac{y}{h}\right) \quad (6)$$

For smooth bed, Nezu and Nakagawa [11] proposed an equation for distribution of turbulent kinetic energy, i.e., k , which decreases exponentially with its maxima at the bed of the channel, i.e.,

$$k/u_*^2 = 4.78 \exp(-2y/h) \quad (7)$$

This paper deals with measurement of temporal variation of the velocity on smooth and rough beds in an open channel using ADV. The velocity distribution, turbulence intensities, and turbulent kinetic energy are computed using the measured velocities. Also, study is done regarding what is the aftermath on various turbulence parameters when an obstruction is placed on the bed of the channel.

2. EXPERIMENTAL SETUP AND PROCEDURE

Experimentation was performed in Hydraulic Engineering Laboratory of Civil Engineering Department of Indian Institute of Technology, Roorkee. The channel was 12 m long and 0.65 m deep and 0.46 m wide. The side walls of the channel were of glass panels and the bed of the channel consisted of steel plate. Depth of flow was controlled by a motorized gate at the end of the channel. Straighteners and flow suppressers were provided in the upstream to stabilize the flow. Velocity and discharge were respectively measured by Acoustic Doppler Velocimeter (ADV) and ultrasonic flowmeter. The experiment was performed for three bed slopes, i.e., 0.00072, 0.00089 and 0.00104. For each slope, experiments were performed for three different discharges and for each discharge, velocity was measured at 10 points along the depth of flow. Three hundred data samples were collected at each point at the sampling rate of 1 Hz. For smooth bed experiment, discharge varied in the range of 0.026–0.046 m³/s and for rough bed 0.0198–

$0.061 \text{ m}^3/\text{s}$. The size of the roughness was $d_{50} = 4.26 \text{ cm}$.

3. ANALYSIS OF DATA

3.1. Velocity Distribution

Variation of dimensionless velocity with frictional Reynolds number, i.e., yu_*/ν for smooth bed and with y/k_s for rough bed are shown in Figure 1. Logarithmic velocity distribution as given in the following equations is also plotted in Figure 1.

For smooth bed

$$U/u_* = 2.5 \log(yu_*/\nu) + 5.5 \quad (8)$$

For rough bed

$$U/u_* = 2.5 \log(y/k_s) + 8.5 \quad (9)$$

From Figure 1(a) and 1(b), it is clear that the observed velocity distribution follow the logarithmic law both for smooth and rough bed.

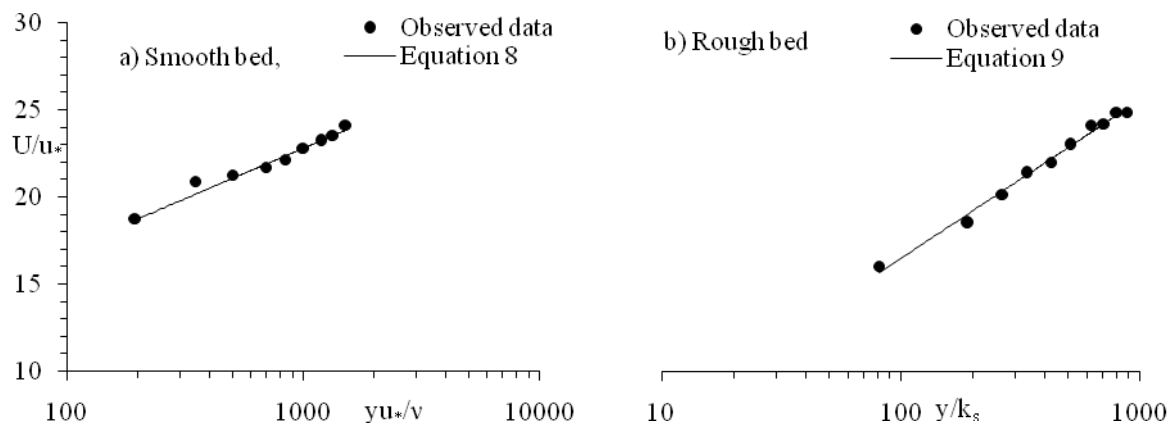


Fig. 1: Velocity Distribution for Smooth and Rough Beds.

3.2. Turbulent Intensities

Variation of turbulent intensities, i.e., u'/u_* , v'/u_* and w'/u_* along the depth is shown in Figures 2 and 3 for smooth and rough beds, respectively. It can be seen from these graphs that the turbulent intensities are more near bed and decrease exponentially in vertical direction. Nezu and Rodi [6] equations for distribution of turbulence intensity as plotted in these figures over-predict the turbulent intensities. New equations for turbulent intensities in x, y and z directions for smooth bed are proposed, which are given below:

$$\begin{aligned} u'/u_* &= 1.47 \exp(-1.04y/h) \\ v'/u_* &= 0.48 \exp(-1.16y/h) \\ w'/u_* &= 0.30 \exp(-0.04y/h) \end{aligned} \quad (10)$$

Nezu and Rodi [6] equations were found to over-predict the turbulent intensities for rough bed also as shown in Figure 3. The equations proposed in this study for the rough bed to compute the turbulent intensities in x, y and z directions with relative depth y/h for rough bed condition, are:

$$\begin{aligned} u'/u_* &= 1.38 \exp(-1.36y/h) \\ v'/u_* &= 0.56 \exp(-1.76y/h) \\ w'/u &= 0.26 \exp(1.48y/h) \end{aligned} \quad (11)$$

Goring and Nikora [9] equations also over-predict the turbulence intensities for rough bed. Compared to Nezu and Rodi [6] equations Goring and Nikora [9] equations were found to be more proximate to the observed turbulence intensities.

Both the Figures 2 and 3 for smooth and rough beds, respectively, indicate that longitudinal, transverse and vertical turbulence intensities are more near the bed and decrease exponentially along the vertical direction. However, vertical turbulence intensity increases in vertical direction for rough bed. Grass [5] had also arrived at the same conclusion.

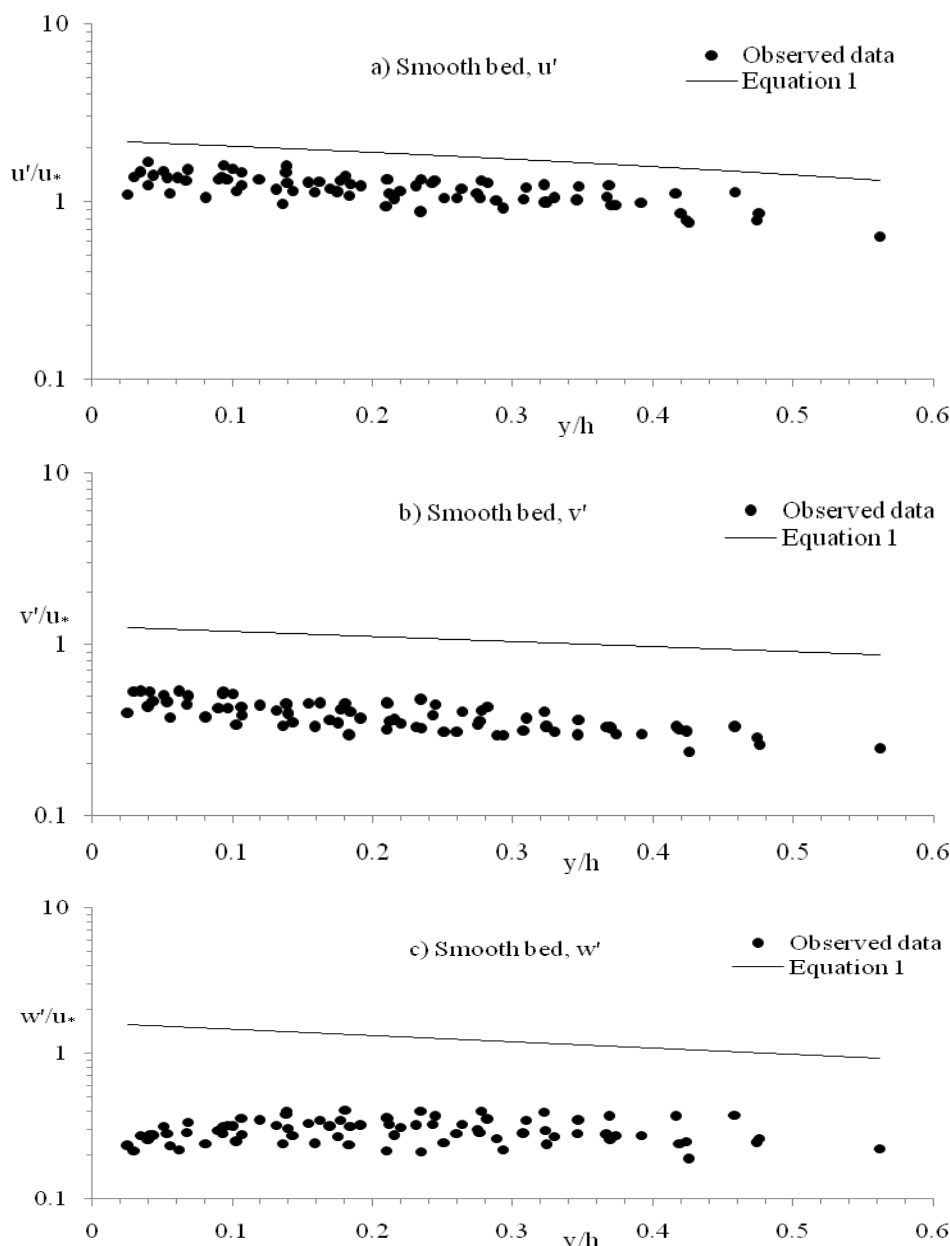


Fig. 2: Turbulent Intensities Distribution in (a) Longitudinal, (b) Lateral and (c) Vertical Directions for Smooth Bed.

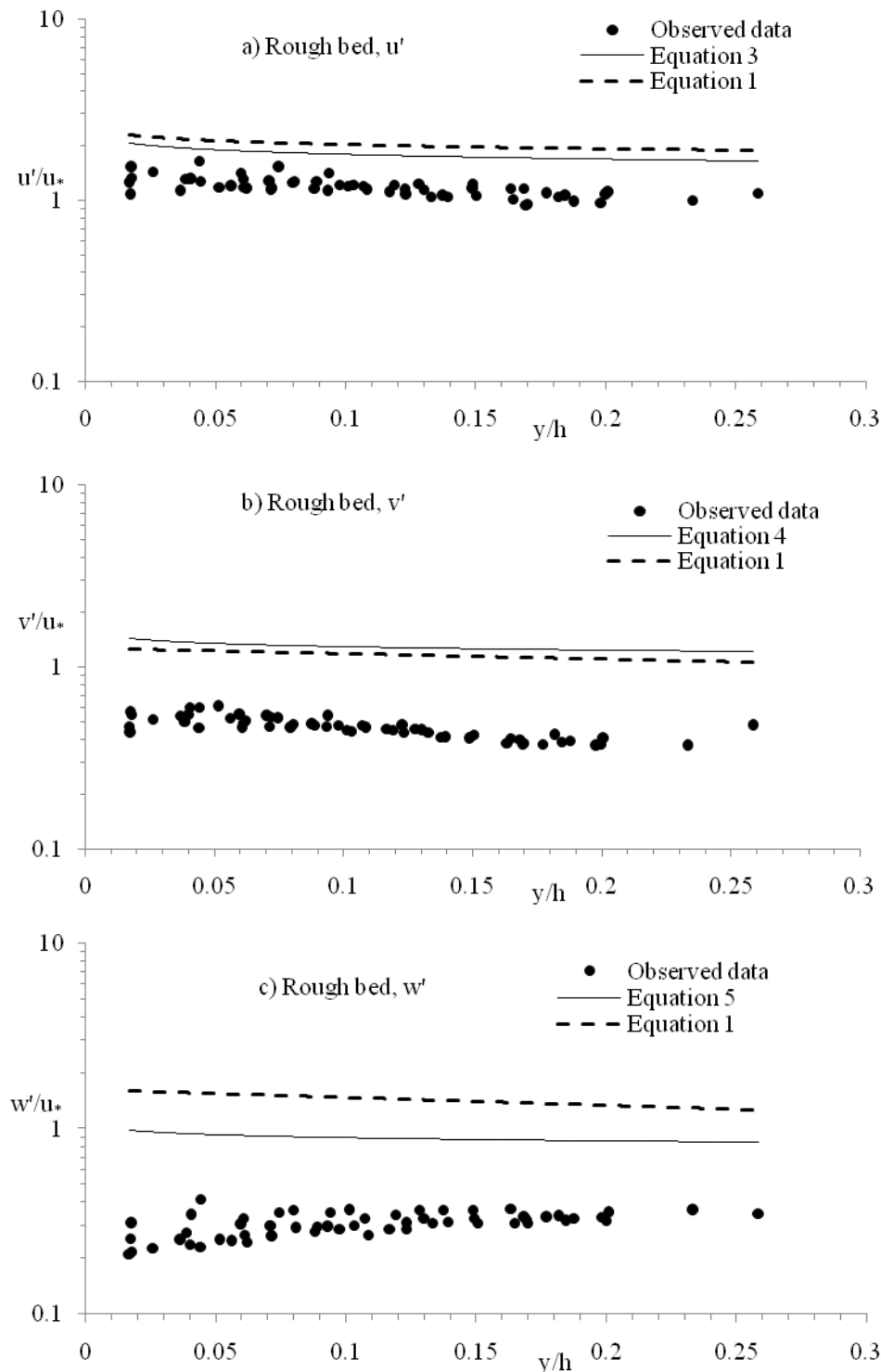


Fig. 3: Turbulent Intensities Distribution in (a) Longitudinal, (b) Lateral and (c) Vertical Directions for Rough Bed.

3.3. Turbulent Kinetic Energy Distribution

Turbulent kinetic energy, i.e., k/u_*^2 for both rough bed and smooth bed was also found to decrease with the relative depth in an

exponential manner. Nezu and Nakagawa [11] equation, was observed to over-predict the turbulent kinetic energy in the flow as shown in Figure 4. Formulae for turbulent kinetic

energy are proposed for smooth and rough bed conditions, respectively:

$$\begin{aligned} k/u_*^2 &= 1.24 \exp(-2.00y/h) \\ k/u_*^2 &= 1.14 \exp(-2.57y/h) \end{aligned} \quad (12)$$

For rough bed, Goring and Nikora [9] and Nezu and Nakagawa [11] equations were

found to over-predict the turbulent kinetic energy. Goring and Nikora [9] equation was found to be more proximate to observed turbulent kinetic energy than Nezu and Nakagawa [11] equation.

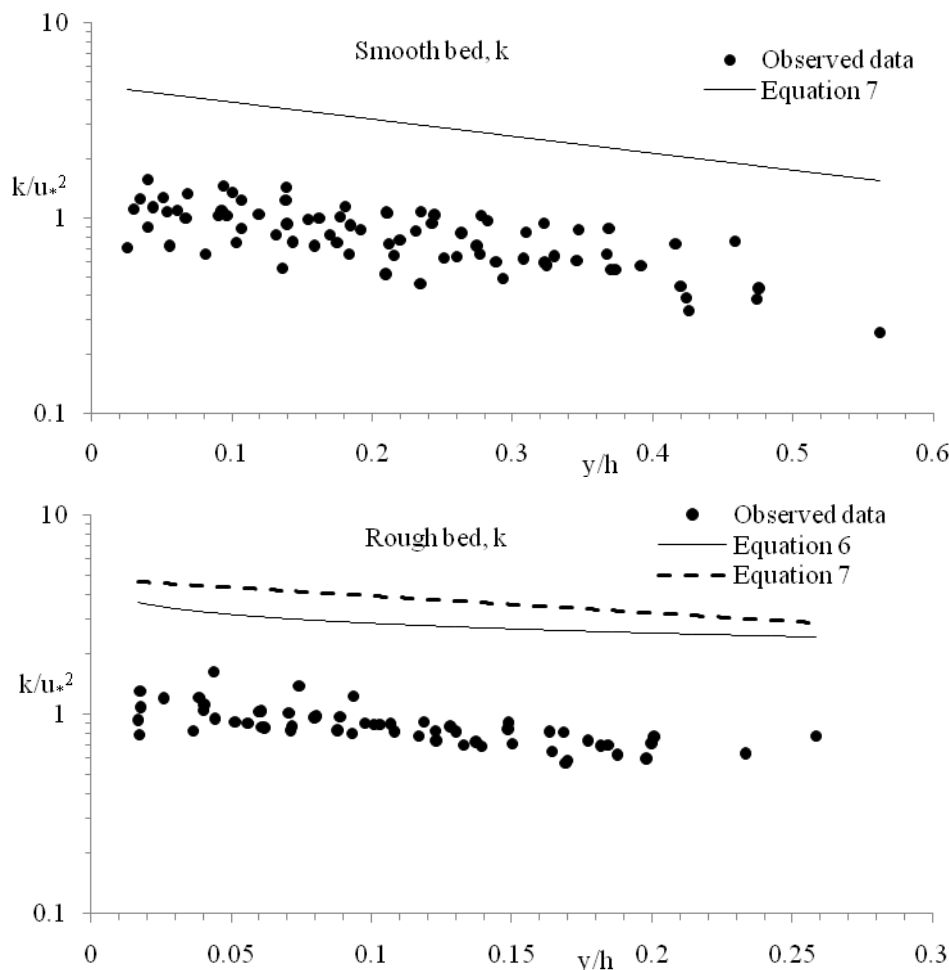


Fig. 4: Variation of Turbulent Kinetic Energy along Depth for Smooth and Rough Beds.

4. CONCLUSIONS

The following conclusions can be drawn from the present study:

1. The measured velocities on both smooth and rough beds were observed to be in accordance with logarithmic law.
2. For both smooth and rough beds, turbulence intensity was found to be more near the bed (except for the vertical turbulence intensity on rough bed) and decreases exponentially in the upward direction. However, vertical turbulence intensity on rough bed is less near the bed

and increases in the upward direction. Nezu and Rodi [6] equations on both smooth and rough beds and Goring and Nikora [9] equations for rough bed were observed to over-predict the turbulence intensity in all directions. .

3. For both smooth and rough beds, turbulent kinetic energy was found to be more near the bed and then decreases along the depth exponentially. Nezu and Nakagawa [11] equation for smooth and rough beds and Goring and Nikora [9] equation for rough bed were observed to over-predict the turbulent kinetic energy.

REFERENCES

1. Pope, S.B. *Turbulent Flow*. Cambridge University Press, 2000. 34-92p.
2. Nezu, I. *Journal of Hydraulic Engineering*. ASCE. 2005. 131(4). 229-246p.
3. Sharma, H. *ADV measurements of turbulence over smooth and rough beds*. Submitted in partial fulfillment of the requirements for the award of the degree Masters of Technology in Civil engineering at Indian Institute of Technology Roorkee. 2009.
4. Blinco P. H. and Partheniades E. *Journal of Hydraulic Research*. IAHR. 1970. 9. 43-69p.
5. Grass A. J. *Journal of Fluid Mechanics*. Cambridge University Press. 1971. 50(2). 233-255p.
6. Nezu I. and Rodi W. *Journal of Hydraulic Engineering*. ASCE. 1986. 112(10). 335-355p.
7. Kirkoz M. S. *Journal of Hydraulic Engineering*. ASCE. 1989. 115(11). 1543-1561p.
8. Steffler P. M., Rajaratnam N. and Peterson A. W. *Journal of Hydraulic Engineering*. ASCE. 1985. 111(1). 119-130p.
9. Goring D and Nikora V. I. *Journal of Hydraulic Engineering*. ASCE. 1998. 124 (6). 630-634p.
10. Wang J., Dong Z., Chen C., et al. *Journal of Hydraulic Research*. IAHR. 1993. 31(1). 89-98p.
11. Nezu I. and Nakagawa H. *Turbulence in Open Channel Flows*. IAHR Monograph. AA Balkema, Rotterdam. 1993.