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Measurement of Turbulent Velocity Fluctuations in Open Channel using Acoustic Doppler Velocimeter

KEYWORDS: Open channel, Acoustic Doppler Velocimeter (ADV), Turbulence, Reynolds shear stress.

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ABSTRACT Entrainment of sediment particles from channel beds into the channel flow is influenced by the characteristics of the flow turbulence which produces stochastic shear stress fluctuations at the bed. These fluctuations can be measured in open channel bed by measuring the instantaneous velocity components. Present study deals with extraction of information related with measurement of instantaneous velocity components which helps in finding turbulence parameters in open channel bed. The experimental work was planned for collection of data related with 3-D instantaneous velocity over the depth in an open channel mobile bed using 3-D Acoustic Doppler Velocimeter (ADV). The instantaneous velocity components and normalized velocity profile on uniform size (2.0-4.0 mm) sediment bed in an open channel flow over rough beds were also presented. The turbulence parameters such as turbulent kinetic energy and Reynolds shear stresses were quantified across the flow depth by measuring the time averaged velocity components.

I. INTRODUCTION

Turbulence in open-channel flow holds both interest and great practical importance. The turbulent processes in rivers strongly influence the velocity distribution, the bed shear stress, energy loss, sediment transport, etc. The understanding and practical aspect of turbulence phenomena in open-channel flow are widely sought. Turbulence measurements in water flows began with the development of Hot-Film Anemometers. The advent of the advanced techniques like Acoustic Doppler Velocimeter (ADV) enabled investigators to measure turbulent quantities accurately in both 2-D and 3-D open channel flows. In turbulent flows main phenomena of momentum transfer depend on the behavior of Reynolds shear stress.

In turbulence, there is fluctuating components of velocity which is required to be estimated in the turbulence parameters. In past, many researchers used mean velocity to describe transport phenomena, however, actual turbulent flow can be described by estimation of fluctuating components of velocity in appropriate directions. Many studies were reported previously for finding the instantaneous velocity components using Hot film anemometer (Nakagawa and Nezu, 1977) and Acoustic Doppler Velocimeter ADV (Keshavarzi and Ball 1997; Song and Chiew 2001; Keshavarzi and Shirvani 2003; Carollo et al. 2005; Keshavarzi et al. 2005; Keshavarzi and Ball 2007; Mazumdar et al. 2011; Ramesh et al. 2011; Keshavarzi et al. 2012; Maity and Mazumdar 2012; Ramesh and Kothiyari 2013; Maity and Mazumdar, 2013) in quantifying the turbulent flow characteristics over channel bed. The present work provides the better understanding of finding 3-D velocity fluctuation components over uniform characteristics sediments in open channel. The objectives of present study are to collect experimental data as flow turbulence over fluvial bed of uniform sediments and quantification of various turbulence characteristics, viz. turbulence kinetic energy, turbulent diffusion and Reynolds shear stresses along the depth of flow in alluvial open channel bed.

II. EXPERIMENTAL SET-UP

In present study, the experiments have been carried out in a tilting recirculating flume in the Advanced Hydraulics Lab of Civil Engineering Department, SVNIT, Surat, India. The flume is of length L = 15.0 m, width B = 0.90 m and depth H = 0.6 m. The photograph of the experimental setup is shown and its accessories are marked in the photo 1. The magnetic flow meter device (1) is used for measuring the discharge. The upstream section (2) of the flume is made with stilling arrangement using two honeycomb cage perforated plates. The sediment feeder (3) is used to insert the sediment. There are two instrument carriages (4) used to fit and hold the pointer gauge and ADV. The flume walls are made of Perspex windows (5). In flume, 6.0 m long working section located at 4.0 m downstream from the flume inlet was used for experimentation to ensure fully developed turbulent flow. The experimentation readings were collected in this working section. There are two trays in sediment trapper (6) to collect the sediments.



Photo 1. Experimental Setup

For controlling the tail gate, there is a lever-arm (7) to open and close the tail gate.At the end of the flume, the tail gate (8) is provided for regulating the depth at the working section. There is volumetric tank (9) of dimensions L=2.195 m, B = 1.985 m and H = 0.960 m at the downstream of the flume. The wooden framework arrangement (10) is fitted on the instrument carriage. The uniform sediment of size 2.0-

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4.0 mm was used to further experimentation. The size sediment was laid in the flume having 9.0 cm thickness along the 6.0 m working section length. The 3-D instantaneous velocity components are measured with the help of Acoustic Doppler Velocimeter (ADV). It is designed to measure the instantaneous velocity components at a single-point with a relatively high frequency. The down looking Sontek ADV is shown in Photo 2.



Photo 2 Down Looking Sontek ADV Mounted on Trolley

The measurements are done by measuring the velocity of particles in a remote sampling volume based upon the Doppler shift effect. The probe head includes one transmitter and three receivers. The remote sampling volume is located 5 cm below from the tip of the transmitter. The sampling volume is about a cylinder of water with a diameter of 6 mm and a height of 9 mm. For each receiver there is a velocity component, a signal strength value, a signal-to-noise (SNR) and a correlation value. The signal strength, SNR and correlation values are used to determine the quality and accuracy of the velocity data. The SNR value should be greater than 15 and correlation ratio should be greater than 70% for better results. For the present study these values are checked and found to be greater than desired value. The Horizon ADV software was given by SONTEK company with the instrument. The software is used to collect and store the velocity measurements from the instrument ADV to the computer. The screen view of Horizon ADV software is shown below in Photo 3.

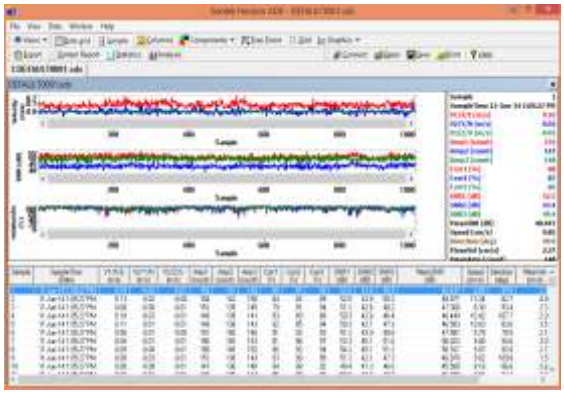


Photo 3 Screen view of Horizon ADV Software

I.EXPERIMENTAL PROCEDURE

Experimental flume was set on desired longitudinal slope. The desired uniform size sediment bed in the present study, as described in previous section, is laid in the flume with 9.0 cm thickness in the working section. Experiments have been started with a low discharge. The discharge is increased slowly; and uniform flow was maintained for given discharge. The 3-D velocity measurements were taken along the depth using ADV at 20 to 23 vertical points. The measurements were taken along the centre line of the flume at two three locations. The experiments were conducted under steady and sub-critical flow conditions. The details of flow parameters, and its ranges are included in Table 1.

TABLE I
Characteristics of Sediment bed and Range of Flow Used in Present Study

SEDIMENT	Q (lps)	S0	y (cm)	Re
Uniform Sediment bed (2mm-4mm)	45.0-60.0	2.0 x10-3	10.5-12.5	5.26x104

IV. FLUCTUATION OF VELOCITY IN TURBULENT FLOW

In turbulent flow, velocity at a particular point shows continuous fluctuation with time. A time averaged velocity at a point is obtained from measurements of velocity at that point for significant interval. The point mean velocity, fluctuating components, instantaneous velocity measurements for a typical sampling interval are shown in Figure 1.

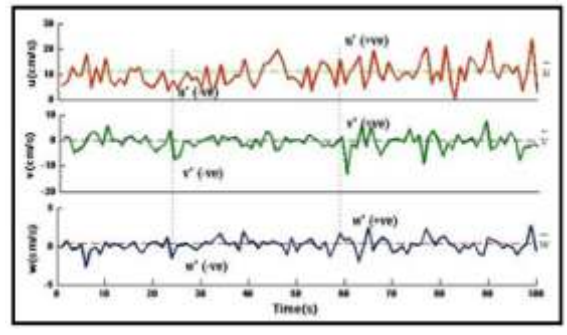


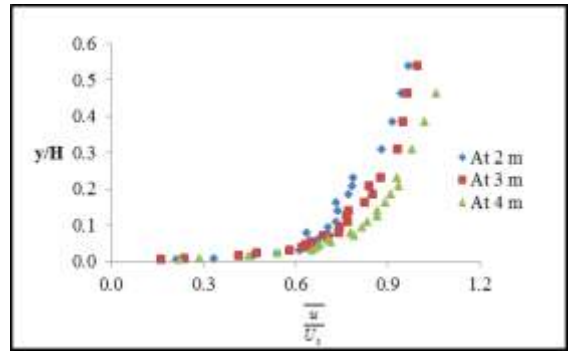
Figure 1 Fluctuations of Velocity Measurements (u′, v′, w′), Mean Velocity and Instantaneous Velocity for experiment at y = 0.05 cm and Q = 60.0 lps

In Figure 1, u′, v′, w′ represent fluctuating components of instantaneous velocity in x (longitudinal), y (transverse) and z (normal along depth) directions respectively. Similarly, $\overline{u}$, $\overline{v}$ and $\overline{w}$ represent mean velocity components in x, y and z directions respectively.

$$u' = u - \overline{u} \;,\; v' = v - \overline{v} \quad \text{and} \quad w' = w - \overline{w} \qquad (1)$$

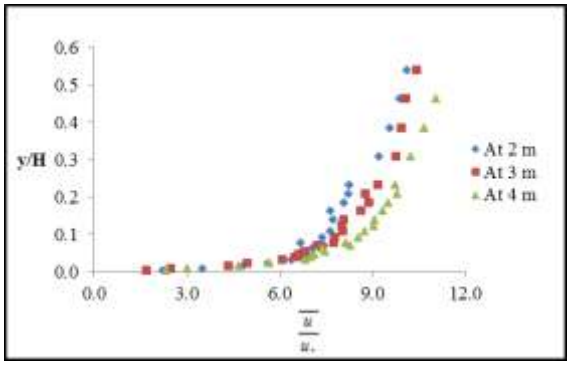
V. NORMALIZED VELOCITY DISTRIBUTION

Normalized velocity profiles, $\frac{\overline{u}}{U_0}$ v/s $\frac{y}{H}$ and $\frac{\overline{u}}{u_*}$ v/s $\frac{y}{H}$ are plotted for measured velocity at distances x= 2.0 m, 3.0 m and 4.0 m from the start of working section, on uniform size sediment bed in Figure 2 (a) and (b) respectively.



(a)

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(b)

Figure 2 Normalized Velocity Distribution for different longitudinal distances along the flow

(a) $\frac{\overline{u}}{U_0}$ v/s $\frac{y}{H}$ (b) $\frac{\overline{u}}{u_*}$ v/s $\frac{y}{H}$

From Figure 2 (a) and (b), it can be seen that most of the data points follow the same trend, means the flow is fully developed in the working section. Here y, H, U0 and u* represent depth of measuring point above bed, depth of flow, average flow velocity & shear velocity in the channel respectively.

Vi. LAW OF WALL FOR UNIFORM SEDIMENT BED

Nikuradse (1933), proposed the velocity distributions over smooth and rough beds as enumerated in Eqs.(2) and (3) respectively for smooth and rough beds.

$$\frac{\overline{u}}{u_*} = 5.5 + 2.44 \ln\left(\frac{u_* y}{\nu}\right) \quad (2)$$

$$\frac{\overline{u}}{u_*} = 5.5 + 2.44 \ln\left(\frac{u_* y}{\nu}\right) \quad (3)$$

The classification of boundary as rough, transition or smooth is based on the following conditions:

- If, $\frac{K_s u_*}{\nu}$ < 5 then it smooth turbulent flow;
- If, 5 < $\frac{K_s u_*}{\nu}$ < 70 then it is transition turbulent flow;
- If, $\frac{K_s u_*}{\nu}$ >70 then boundary is rough turbulent flow.

Here, K_s is equivalent sand grain roughness, ν is kinematic viscosity of water and u* is shear velocity for flow under considerations and computed as $\sqrt{\tau_0 / \rho}$

Eq. (2) is plotted in Figure 3, along with observed experimental data for present study. The value of $\frac{K_s u_*}{\nu}$ is found to be 262.2 and it is found that flow was hydrodynamically rough for the experiments.

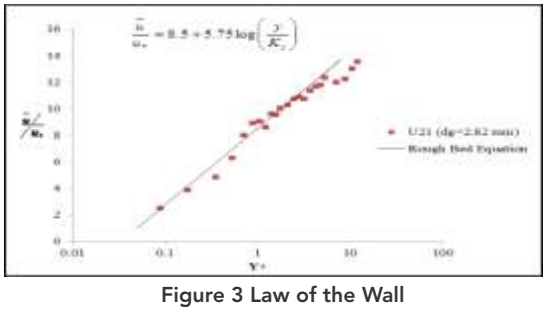


Figure 3 Law of the Wall

VII. TURBULENT KINETIC ENERGY (T.K.E)

The T.K.E is estimated for uniform sediment bed for same flow conditions. It can be represented as:

$$T.K.E = \frac{1}{2}(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}) \quad (4)$$

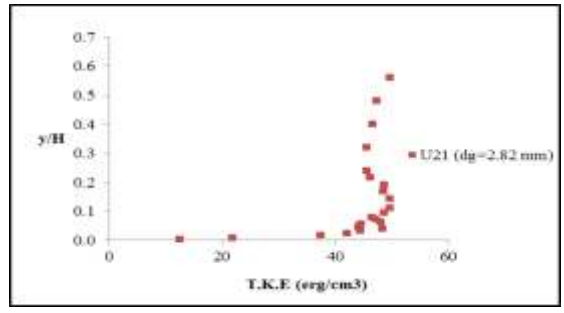


Figure 4 Turbulent Kinetic Energy From

Figure 4, it is seen that turbulent kinetic energy increases with depth near the bed region; and then decreases at y/H=0.10 in open channel.

VIII. NORMALIZED REYNOLDS SHEAR STRESS

Normalized Reynolds Shear Stresses were estimated from the Eq. (4). The normalized shear stress for the experiment undertaken in the present study on uniform sediment bed and is shown in Figure 5. It can be represented as:

$$\tau = -\rho \overline{u'w'} \quad (5)$$

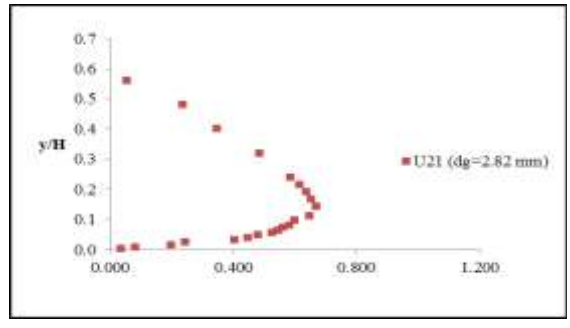


Figure 5 Normalized Reynolds Shear Stress From Figure

5,it is seen that normalized Reynolds shear stress increases marginally near the bed upto y/H <0.10 and decreases at higher depths afterwards.

IX. CONCLUSIONS

The ADV has proven to be a versatile and accurate 3-D velocity sensor suitable for most applications in turbulence measurements. The overall assessment shows that ADV has added benefits of providing full three-axis velocity measurement with better accuracy. It is seen that most of the data follows the typical velocity distribution pattern. For present study, shear Reynolds number ks+ has been found to be greater than 70.0, hence flow condition has been considered as rough turbulent flow. The flow is sub-critical as the value of Froude number is less than 1.0. The turbulence characteristics such as turbulent kinetic energy and Reynolds shear stresses across the flow depth on uniform sediments bed in open channel are quantified.

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