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Research paper

Turbulence statistics of flow through degraded channel bed of sand–gravel mixture

Rajesh K. Jain [a], Ashish Kumar [b,*], Umesh C. Kothyari [c]

[a] *Department of Civil Engineering, Government Engineering College, Chandkheda, Gandhinagar, Gujarat, India*

[b] *Department of Civil Engineering, Jaypee Univ. of Information Technology, Waknaghat, Solan, H.P., India*

[c] *Department of Civil Engineering, Indian Institute of Technology Roorkee, India*

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Abstract

This paper describes the results of an experimental study on the turbulence characteristics of flow through bed profile of a laboratory channel that was degraded by detachment of its bed material consisting of sand–gravel mixture. The measurements of velocity and turbulence characteristics over the degraded bed profile were made at three locations along the degraded bed profile using an ADV. The maximum value of turbulence intensity and the Reynolds shear stress were found to occur at the level of bed surface existing before the detachment and these values decreased towards the flow surface. The magnitude of turbulence intensities and Reynolds shear stress are observed to reduce, as one moves towards the downstream along the degraded bed profile which signifies that vortex structure weakened by bed profile degradation. Quadrant analysis was performed which demonstrated the importance of ejection and sweep phases in sediment detachment and transport. Highest occurrence probabilities are found for sweep and ejection event. The other two events i.e. outward and inward interactions are found to have very small occurrence on the probabilities. Variation of occurrence probability with hole size (*H*) is also discussed.

Keywords: Turbulence; Detachment; Sediment transport; Quadrant analysis; Cohesionless sediment; Acoustic Doppler Velocimeter

1. Introduction

The knowledge of detachment and transport process of sediment is necessary for solving various problems like soil erosion in catchments, reservoir sedimentation, stable channel design, river morphological computations etc. In most of alluvial rivers, the sediment transport is usually accompanied with formation of bed forms and flow resistance and turbulence statistics of such flows are different from the flow through the streams having plane bed. Turbulence is one of the main controlling factors which determine the character and intensity of river process. Understanding of turbulent flow structure and its relation with process of sediment transport mechanism is also needed for predictions of river bed degradation. The turbulent open channel flows with mobile granular beds have complex boundary conditions due to effects of bed mobility and permeability (Nikora and Goring, 2000). The dynamics of sediment suspension in the fluvial environment is strongly influenced by the turbulent flow structures (Sutherland, 1967; Nelson et al., 1995). Different boundary conditions in case of mobile bed flows make turbulent flow structure to be different in flow through erodible beds than flows in fixed bed streams. This aspect has been much less studied by the researchers compared to the turbulent open channel flow over fixed beds. Therefore in present study the turbulence characteristics of flow through degraded profile of channel bed of sand–gravel mixture are investigated by using an Acoustic Doppler Velocimeter (*ADV*).

* Corresponding author.

E-mail addresses: rajkjain7@gmail.com (R.K. Jain), ashish.fce@gmail.com (A. Kumar).

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2. Brief review

Over the past decade several researchers have used an *ADV* to study the velocity distribution and turbulence characteristics of flow phenomenon in channels without any obstruction as well as alteration in the flow structure caused by some obstruction like piers, abutments etc. Schoppmann (1975) measured stream-wise turbulence intensity in scour holes downstream of a wedge and reported that turbulence intensity decreased as scour hole developed and a peak in the turbulence intensity occurred at the point of flow reattachment. Song and Graf (1996) presented velocity and turbulence distribution in unsteady open channel flow. They varied the flow discharge by passing a flow hydrograph through the laboratory channel and concluded that turbulence intensity and the Reynolds stress are larger in rising branch of hydrograph as compared to falling branch. Wijetunge and Sleath (1998) studied effect of sediment transport on the fluid velocity and turbulence using Laser Doppler Anemometer (*LDA*). With sediment in motion they observed reduction in turbulence intensity at any given height compared to flow over fixed bed under flat bed conditions. Shen and Lemmin (1999) measured mean velocity, velocity variance, the Reynolds stress using an acoustic particle flux profiler (*APFP*) in a particle laden open channel flow. Two kinds of coherent structure, the ejection and the inrush are found to be dominant in the outer region which are responsible for particle entrainment, re-suspension and deposition. Nikora and Goring (2000) compared turbulence intensity and the Reynolds stress in an irrigation canal in two types of flow conditions viz; fixed bed and weakly mobile bed. The turbulence intensity, the Reynolds stress and high order velocity moments having similar variation were noticed in these types of flow.

Shvidchenko and Pender (2001) experimentally studied the turbulent structure of open channel flow over various sized gravel bed channels. Lift and drag hydrodynamic force generated due to eddy motion of fluid is considered to be responsible for movement of fluid particles in sediment bed based on the experimental observations. Song and Chiew (2001) measured mean turbulence characteristics in equilibrium non-uniform open channel flow. The turbulence intensity and the Reynolds stress were noticed to be different in such flows as compared to the uniform flow. Graf and Istiarto (2002) studied flow pattern in the scour hole around the cylinder experimentally. They concluded that strong turbulence is formed in the rear of the cylinder. Kumar and Kothyari (2012) measured the flow pattern and turbulence characteristics around the circular uniform and the compound piers within the developing (transient stage) scour hole using an ADV.

Carrollo et al. (2002) studied flow measurement over flexible bottom vegetation. They used 2-D *ADV* to measure local flow velocities with varying vegetation concentrations, discharges and channel slopes. They concluded that all measured velocity distributions are S-shaped and exhibit a three zone profile. However they also observed that stem concentration affects the shape of the velocity profile. Liriano et al. (2002) conducted experiments over uniform size grave placed in the channel bed and reported a series of experiments within scour hole that was fixed at different stage of development. They investigated mean velocities, turbulence intensities and the Reynolds stresses in scour holes and concluded that, as scour hole develops the Reynolds stress and turbulence intensities reduce in magnitude.

Cellino and Lemmin (2004) studied the influence of suspended sediments on coherent flow structures using *APFP*. They carried out the measurements in clear water flow and particle-laden flow. They investigated the predominance of ejection and sweep phases in sediment resuspension and transport as noticed in this study also. Tritico and Hotchkiss (2005) studied turbulence characteristics in two gravel bed rivers using an *ADV*. They collected data as unobstructed flow and in the wake of emergent boulders. They noticed considerable difference in measurements of mean velocity, turbulent kinetic energy, the Reynolds stress in case of obstructed flow compared to unobstructed flow. Mazumder and Ojha (2007) illustrated turbulence statistics of flow due to wave–current interaction which is also done in present study in straight channel flows. Also as in the present study, the quadrant analysis was made to investigate the importance of bursting events contributing to the Reynolds stress in the near bed region. Dey and Raiker (2007) reported experimental results of turbulence flow characteristics over loose rough boundaries at near threshold of sediment motion. They measured and analysed turbulence intensities and the Reynolds stress. They concluded that turbulence intensities can be defined by an exponent law and the Reynolds stress distribution is linear with depth. Rodriguez and Garcia (2008) studied secondary circulation and flow variability in straight open channel over a rough bed. They measured 3-D velocities and turbulence characteristics using a micro *ADV* and reported that bed shear stress and turbulence patterns were consistent with the secondary flow cellular circulation. The review thus indicated that no study has been conducted as yet to describe the flow and turbulence characteristics of flow through channel bed profile degraded due to detachment of sand–gravel mixture.

3. Experimental programme

3.1. Experimental flume and material

The experiments have been conducted in a 16 m long, 0.75 m wide and 0.5 m deep tilting flume located in the Hydraulic Engineering Laboratory of Civil Engineering Department, Indian Institute of Technology, Roorkee, India. The flume has a test section of 6.0 m long and 0.75 m wide starting at a distance of 8.0 m from channel entrance and sediment mixture was filled in the test section up to the depth equal to 0.13 m. Obse-rvations were made at various slopes of flume ranging from 2.417×10^{-3} to 5.8×10^{-3}. The discharge in the flume was provided by a constant head overhead tank. The measurement of discharge is made volumetrically with the help of a tank provided just after downstream end of the channel. The water supply into the flume was regulated with the help of a valve provided in the inlet pipe. Uniform sand