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Turbulence characteristics of flow region over a series of 2-D dune shaped structures

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Abstract

This paper addresses the development of a flow region associated with turbulence and stress characteristics over a series of 2-D asymmetric dunes placed successively at the flume surface. Experiments were conducted over twelve asymmetric dunes of mean length 32 cm, crest height 3 cm and the dune width almost as wide as width of the flume, using 3-D Micro-ADV at the Indian Statistical Institute, Calcutta. The variations of turbulence statistics along the flow affected by the wavy bottom roughness have been studied. Quadrant decomposition of the instantaneous Reynolds shear stress has been adopted to calculate the contribution of ejection and sweeping events in shear stress generation. The relative dominance of two events are found to contribute in a cyclic manner (spatially) in the near bed region, whereas such phenomenon seems to be disappeared towards the main flow.

Keywords: Turbulent boundary layer; Dunes; Flow separation; Reynolds stress; ADV; Conditional statistics

1. Introduction

Dunes are the most common bed form structures in sandy rivers. Knowledge of the turbulence characteristics of the complex flow regimes found over typical bed forms or dunes must be known to predict the behavior of many natural phenomena. Dunes in bed load-dominated and/or laboratory environments are often asymmetric having low-sloping upstream side (stoss) and steep lee faces [12,17], while those in suspended load dominated environments are often more symmetric with relatively low angle lee faces [19,3]. The bed forms, such as ripples and dunes, play an important role in controlling sediment transport rates, generating turbulence and creating flow resistance, so it is essential that a detailed understanding be acquired of turbulence characteristics over two dimensional dunes. Experimental and field investigations of dunes have documented the macro-turbulent characteristics of spatially varied flow over the bed forms called "kolks" and "boils" proposed by Matthes [25]. The "kolks" and "boils" are the upward tilting vortices of both fluid and sediment originated from downstream of dune crests and at the point of reattachment. On the basis of the observation on "kolks" proposed by Matthes, Sengupta [36] suggested that such action in the stream bed might be responsible for initiation of trough type cross-beddings in river beds. Several experiments were performed to estimate the resistance to the flow due to the physical changes of bed forms generated by the turbulent flow [34,10]; and others. Wiberg and Nelson [41] conducted the laboratory experiments under unidirectional flow over asymmetric and symmetric features including high-angle and low-angle ripples. Lyn [21] reported the experimental study on the mean flow and turbulence characteristics over artificial space-periodic one-dimensional bed form features using 2-D laser Doppler velocimetry (LDV). Bennett and Best [1] suggested that the bursting events due to turbulent flow are associated with the zone of Kelvin–Helmholtz instabilities developed at the zone of flow separation in front of ripple lee. Venditti and Bennett [40] used the spectral and co-spectral analysis

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to describe the characteristics of turbulent flow and suspended sediment transport over fixed dunes. Best et al. [2] performed a field study at the Fraser River Estuary, Canada followed by the experimental study in the laboratory using ADVP to provide detailed quantitative visualisation of flow fields associated with natural sand dunes. The structure of mean flow and turbulence over the fixed, artificial, asymmetric, three-dimensional dunes in laboratory channel has been studied by Maddux et al. [22,23]. Best [4] has made an excellent review to summarize the features of mean flow, turbulence, morphology and sediment transport associated with the river dunes and highlighted the future directions of research to understand the dynamics of dunes. The motivation of this study was to determine the spatial changes of flow and turbulence over bed forms, and to gain better understanding of the physics of flow, which are responsible for sediment size sorting and transportation.

In spite of the considerable work mentioned above, little attention has been paid to the development of rough-bottom turbulent boundary layer thickness associated with the turbulence statistics of flow over a series of asymmetric dunes placed consecutively at equal distance. In order to achieve a general output regarding the turbulence accumulating along the flow over series of dunes, it is desirable to analyse the physics of turbulence from the velocity data collected using ADV at different stream-wise locations. Therefore, the present study addresses how the turbulence characteristics of flow vary along a series of static dunes. It also elucidates how the conditional shear stress statistics characterizes the reattachment points in the flow over a trough region. The deviations of velocity, turbulence and the fractional contributions of burst-sweep cycles to the total shear stress due to the presence of dune covered topography would require substantial investigations. The approximation of 2-D static dune configuration is justified because the speed of the sand dunes is small compared with the mean flow. Moreover, the use of fixed bedforms allows a high spatial resolution of analysis and sampling very close to the boundary which is not possible with mobile bedforms. The mobility of the bedforms governs the turbulence near the boundary and hence the transition of the bedforms. In the field, reliable velocity measurements in the lee side of the dune is very difficult. The contamination in data or loss of data leads to overestimation of spatially averaged velocity over the dunes and hence the overestimation of shear stress in this region [18]. Robert and Uhlman [35] performed an experimental study to understand the processes of ripple-dune transition in the laboratory. In order to avoid the difficulty of velocity measurement during the ripple-dune transition they moulded three kinds of bedform features created under mobile flow conditions and performed experiments by fixing those moulded structures in the laboratory. Although the fixed bedform is not a correct representation of the natural dunes, the study over fixed dunes will improve the understanding of turbulence over dunes. The use of fixed bedforms allows the detail study of flow without added difficulty of measurement over mobile bed. Smith and McLean [37] reported from the field that in bed load dominated environment sand waves are relatively steep and very asymmetric, while in the suspended load dominated case they are more elongated and more symmetrical. The fixed dunes in the present study can be assumed to mimic the equilibrium dunes found in the bed load dominated environment. As the bed forms observed in the flume studies involve complex geometry, a train of asymmetric dunes have been chosen to elucidate the essential mechanism of the flow and circulation patterns over the waveform structures. This study addresses the spatial changes of flow characteristics and turbulent events associated with the burst-sweep cycle over the train of waveforms. It aims at improving the understanding of the phenomena which are crucial for the process of sediment transport, upliftment and grain-sorting.

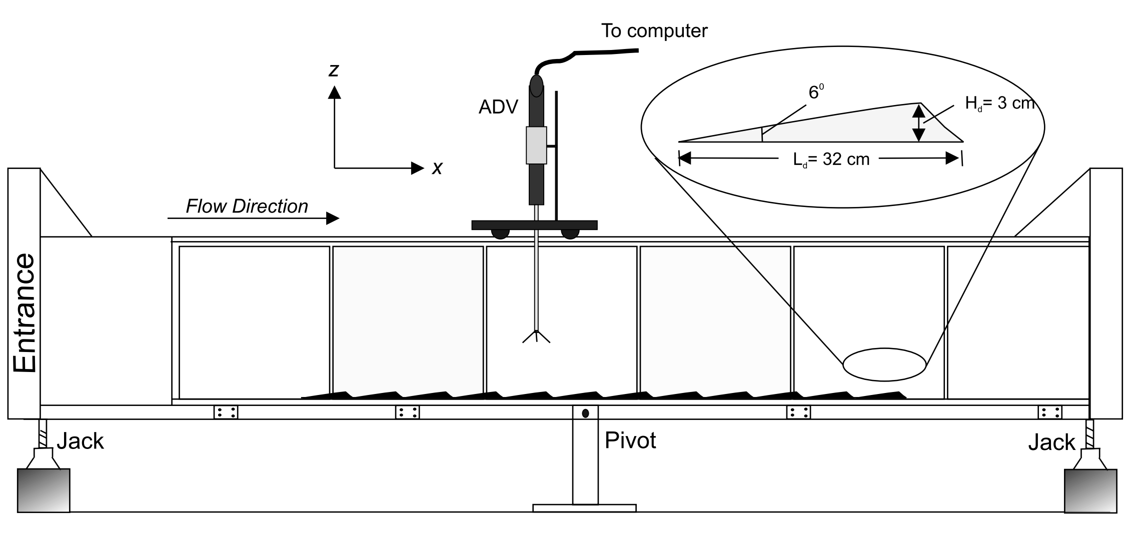

Fig. 1. Schematic diagram of the experimental setup.