Conditionally Averaged Turbulent Structures of Flow over Two Dimensional Dunes in Large Rivers

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Abstract: - This paper investigates the structure and behaviour of time averaged turbulent profiles over a train of 2D asymmetric dunes placed successively on the flume bed. A series of experiments were conducted over 50 asymmetric dunes of mean length 32cm, crest height 3cm and the dune width similar to the width of the flume, using 3D Sontek Micro ADV at the University of Wollongong, Australia. Under similar conditions, the experiments were conducted in the plane bed as well. The acquired data in the plane bed were analysed using Yang’s approach on the division of the vertical velocity fluctuation into upward and downward conditions, in which the conditionally averaged momentum equations were derived. Using these observations, the variations of time and spatially averaged turbulence characteristics along the entire length of a single dune have been studied, specifically in the crest and trough regions, with comparison to the plane bed. It is found out that the mean flow turbulence and stress characteristics over the crest and the trough of a dune behave in a similar manner to the conditionally averaged turbulence and stress characteristics over the plane bed. Further it is found out that the contribution of ejection and sweeping events in shear stress generation is directly associated with the characteristics of the dune. This paper elucidates a very important phenomena in large rivers associated with bed form structures.

Key-Words: - Turbulent flow, Flow separation, Dunes, ADV, Conditionally averaged flow, Reynolds stress

1 Introduction

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. Matthes (1947) investigated the ‘kolks’ and ‘boils’ associated with the flow over dunes. They are the upward tilting vortices of both fluid and sediment originated from downstream of dune crests and at the point of reattachment. Several experiments were performed to estimate the resistance to the flow due to bed forms (Engelund et.al, 1982). The structure of mean flow and turbulence over the fixed, artificial, asymmetric dunes in laboratory channel has been studied by Maddux et al. (2003). Best (2004) 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.

On the other hand, with the advancement of experimental techniques it was revealed that, turbulence irrespective of whether it’s associated with rough or smooth bottom, is dominated by powerful structures that are well organised and ordered eddies termed as “coherent structures”. These can be categorised into two as, “bursting phenomena” that occur in the wall region and “large scale vortical motions” that occur in the outer region. In order to analyse these structures the method of quadrants has been adapted by many researchers, based on the measured velocity fluctuations. i.e. quadrant I, u’>0 and v’>0;
quadrant II, u’<0 and v’>0; quadrant III, u’<0 and v’<0; and quadrant IV, u’>0 and v’<0

Even though investigations on coherent structures have been intensively carried out over the last decade, their interpretation with rough bottom mean flow structure is still limited. In spite of the considerable work mentioned above with regards to the dunes, little attention has been paid to the development of the relationship between coherent structural analysis and the turbulence statistics of flow over a series of asymmetric dunes placed consecutively at equal distance. Thus it is interesting to know the differences or similarities between flow over dunes with time averaged motion and flow over plane bed with conditionally averaged velocity fluctuations.

2 Concept Development
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 describes how the conditional shear stress statistics characterizes the reattachment points in the flow over a trough region. Although the fixed bed form is not a correct representation of the natural dunes, the study over fixed dunes will improve the understanding of turbulence over dunes. A train of asymmetric dunes have been chosen to represent the essential mechanism of the flow and circulation patterns over the waveform structures.

Hence the objectives of this study can be outlined as follows.
1. Obtaining the spatial changes of flow characteristics over the train of dunes
2. Compare the turbulent characteristics in the events of v’>0 and v’<0 in the plane bed, with the mean flow structure over dune covered bed
3. Exploring how the conditional distribution of Reynolds shear stress characterizes the reattachment points in the flow over a trough region

This study aims at improving the understanding of the phenomena, which are crucial for the process of sediment transport, upliftment and grain-sorting.

3 Experimental Details
The experiments were carried out in a specially designed re-circulating flume, which is consisting of the experimental channel, head tank and the tail tank. The channel is 16m long, 0.3m wide and 0.45m high. The experimental walls of the flume are made of glass providing a clear view of the flow. One centrifugal pump providing the flow is located outside the main body of the flume. The outlet pipe is fitted with one by-pass pipe and a valve, so that by adjusting the valve in the outlet, the flow can be controlled at a desired speed. A honeycomb cage is placed at the entrance of the channel to ensure the smooth, vortex free, uniform flow of water through the experimental channel. An electromagnetic discharge meter with a digital display is fitted with the outlet pipe to facilitate the continuous monitoring of the discharge. To ensure the same operating conditions in different experiments the water depth and the discharge are kept constant for all experiments.

After carrying out the experiments on the plane bed, a total of 50 artificial 2-D dunes made of Perspex were fabricated and placed consecutively on the bottom surface of the flume. Acoustic Doppler Velocimeter (ADV) was used for velocity measurements. The dunes had mean wavelength, \( \lambda = 32 \) cm and mean height \( \delta = 3 \) cm at the crest which results in the steepness, \( \delta / \lambda = 0.094 \), which is consistent with values of \( \delta / \lambda \) for real dunes in field (Gabel, 1993). The angles of the stoss side and lee side slope of the dunes were approximately 60° and 50°, respectively. The width of each dune was similar to the width of the flume. The counting of the dunes starts from the very first dune at the upstream end, which is the beginning of the channel inlet, just after the front side of honeycomb. All together thirty different
measuring locations from upstream to downstream along 15 dunes, starting from the crest of the 18th dune, which was located 5.64m from the channel entrance, were carried out. (now we will consider the 18th dune as Dune No.1 as the measurements commences from that. The subsequent dunes follow this numbering approach). The measurements were undertaken by means of SonTek 16MHz 5 cm down-looking 3-D-Micro ADV at the centerline of the channel. The ADV has been validated with several other devices by several investigators and has been used in a variety of applications for turbulence measurements. The velocity data were collected for 2 minutes each at the sampling rate of 25 Hz, with the lowest point in each profile being 0.20 cm above the flume bed surface and with the highest point being about 20 cm for each profile. The mean flow depth h is kept constant at 25 cm for all tests. For each experiment, the velocities were measured at the centreline at about 30 vertical positions. Here, the experiments were performed at a discharge Q = 0.04 m$^3$/sec. While doing experiments over the dune covered bed the flow conditions are kept same as on the flat surface.

4 Experimental Analysis
The velocity data collected by ADV are analysed to compute the mean flow and turbulence characteristics at each point. The time averaged stream-wise velocity, vertical mean velocity, stream-wise turbulence intensity and vertical turbulence intensity are defined as follows.

\[ \bar{u} = \frac{1}{n} \sum_{i=1}^{n} u_i \]  
(1)

\[ \bar{v} = \frac{1}{n} \sum_{i=1}^{n} v_i \]  
(2)

\[ \sqrt{\bar{u}^2} = \sqrt{\frac{1}{n} \sum (u_i - \bar{u})^2} \]  
(3)

Where n is the total no.of velocity observations at each point. The time averaged Reynolds shear stress at a point is determined using

\[ \bar{u}'v' = \frac{1}{n} \sum_{i=1}^{n} (u_i - \bar{u})(v_i - \bar{v}) \]  
(5)

The results of the experiments on flat surface are are in good agreement with previous work (Nezu and Rodi, 1986). Here the parameters are normalized by the friction velocity $u_*$ and analysed against the non-dimensional distance $y/h$.

4.1 Turbulence Intensities and shear stress over the dunes in the Mean Flow
The vertical profiles of stream-wise turbulence intensity component at different streamwise locations, X (in the flow direction) are plotted in Fig. 1a for the trough and in Fig. 1b for the crest locations. It is observed from the figures that, even though the stream-wise turbulence intensity profiles at the trough locations are less than that in the plane bed, it’s gradient first increases with height near the bed with maximum at $y/h = 0.1$ and then decreases with minimum up to the level $y/h<0.2$. Thus, it is interesting to note that the rate of increase of turbulence intensity gradually increases along the flow due to the accumulation of turbulence generated from the series of dunes, which clearly shows the deviations of the turbulence intensities from the reference intensity at the plane surface.

It is observed that the shear stress increases upwards with downstream distance from the first dune. Maddux et.al (2003) found out that, the larger maximum stresses are located along the shear layer above the crest level. Observation reveals that shear stress increases significantly at crest locations and decreases at the trough compared with that for the plane surface. The shear stresses increase upwards with the distance X representing higher turbulence. It is observed that the maximum shear stress attains at the separation point for the trough locations. It is interesting to note that unlike the velocity and turbulence intensity profiles that approach an equilibrium state with distance downstream, the shear stress profiles continue to vary along X.
conditionally averaged flow over plane bed

4.2 Conditionally Averaged Flow over plane bed

When trying to build up the linkage between coherent structures and mean flow structures, Cellino and Lemmin (2004) realised that the most notable feature of turbulence is the fluctuation in wall normal direction, hence they concluded that the turbulence has 2 events, \( v' > 0 \) and \( v' < 0 \). They introduced the conditionally averaged flow in terms of upflow and downflow depending on the wall normal velocity fluctuations, which can be directly linked to the quadrant analysis in coherent structures. Following their approach, Yang (2009) developed conditional momentum equations in the events of upward and downward motions and he clearly described how the conditional distributions of Reynolds Shear Stress and Turbulent Intensities deviate from the expected distribution of the respective mean flow structure. He clearly explained the reasoning behind such behaviour, which brought answers to many mysterious hydraulic questions such as the velocity deviation from the log law and wake function.

Thus it was concluded that in the plane bed, the turbulent features of conditionally averaged flow are totally different from its respective time averaged mean flow. But not any attempt was made to investigate, if the conditionally averaged flow over a plane bed corresponds to any relationship with its respective time averaged mean flow over the same bed, when it’s covered with roughness elements.

4.3 Development of the linkage between mean flow and conditional statistics

The vertical profiles of mean velocity components at the trough and crest points along the stream-wise direction illustrate the characteristic features of turbulent flow. Fig. 2 shows streamwise mean velocity profiles at the trough and crest points, respectively, of each dune.

In order to highlight the relative changes of turbulence parameters, a comparative study has been made between the time averaged velocity profiles at the flat surface and that observed at the trough and crest positions together with the conditionally averaged velocity profiles in the flat surface. It can be clearly noted that, the time averaged velocity profiles over the dune covered bed is almost collapsing on the conditionally averaged velocity profiles over the flat bed. This is a very interesting observation as many researchers have tried to explain the coherent structures with a time averaged analysis, but failed in many of their attempts. Even though the behaviour of the time averaged analysis and the conditionally averaged analysis is quite different with regards to the flat bed, it’s thus interesting to find out with the presence of roughness elements, the time averaged analysis actually envelops the ejection and sweeping phenomena. Generally three distinct layers can be observed in a flow field: (1) internal layer, \( y/h < 0.05 \); (2) the advecting and diffusing region, \( 0.05 < y/h < 0.15 \); and (3) the outer flow region, \( y/h > 0.15 \). For a better view of the flow region at the trough position, the near bed profiles have been analysed. It can be noted that near the boundary in
the inner layer, the time averaged velocity profile of the flat bed actually coincides with the conditionally averaged velocity profile. Thus this continues for the profiles over the dune as well. This is much more prominent when it comes to further downstream dunes. This observation leads to the conclusion that the further downstream the turbulent boundary layer develops over the dune covered bed. It appears from the Fig. 1 that the existence of flow separation, flow reversal and sudden expansion significantly occurs.

**Fig.2: Influence of bed forms on streamwise velocity profile, showing that \( u \) over dune crests is greater than \( u \) over dune trough.**

Some scattering of the data is observed at height \( 0.16 < y/h < 0.2 \) in the stream-wise mean velocity profiles at the crest locations, which may be attributed due to the flow separation. It is observed that at the crest level the horizontal velocity at the crest and the trough locations is smaller than that on the plane surface at that level. Flow is directed upward over the stoss side of the dune and downward past the crest into the trough. The occurrence of greatest upward velocity at the crest is likely to be responsible for the increase in stream-wise flow over the crest (Fig. 2). Just after the crest position strong downward flow occurs which leads to decrease the stream-wise velocity (Fig. 2). The distance between the point of separation and the point of reattachment should be about 5.8δ, which agrees well with Ojha and Mazumder (2008).

### 4.4 Turbulence Intensities and Shear Stress over the Conditionally Averaged Flow

Fig. 3 clearly shows that conditionally averaged Reynolds Shear Stress clearly deviates from its expected linear distribution in the time averaged flow. This can be attributed to the additional momentum flux caused by the conditional upward and downward velocities. In other words upflow (\( v' > 0 \)) promotes the shears stress creating a convex profile, while the downflow (\( v' < 0 \)) suppresses the shear stress creating a concave profile. In terms of coherent structures this can be explained as ejection event and sweeping event respectively. It is also quite noticeable that the Reynolds shear stress profile at the dune crest behaves similar to the upflow, while the profile at the dune trough envelops the down flow. From this observation we can see that, the dominance of sweeping and ejection events are quite significant over the dune covered bed. According to the previous studies mentioned above, the sweeping event s are dominant in the near wall region, while ejections are dominant away from the boundary. This is clearly rationalized from the experimental observation. It is interesting to note that at the dune surface the sweeping events are dominant throughout the dune length except at the trough location, which is closer to the wall region, where ejections take the prominent role. Ojha and Mazumder (2008) carried out intensive experiments on this area and found out that the relative dominance of ejection and sweeping events vary in an oscillatory pattern near the bottom, but at outer region such patterns become weak. They also found out that the sweeping events are dominant in the separation region. (0.6δ. in their case)

**Fig.3: Comparison of conditionally averaged shear stress profile over plane bed with time averaged profile over dunes**
intensity. More importantly, deviations of data points from the solid lines in Fig. 4 is proportional to the deviation of Reynolds Shear Stress. In other words, the positive deviation in Figures 3 and 4 is caused by upward velocity, which illustrates the ejection event and the negative deviation is dominated by the downward motion, which is identical to the sweeping event. It is thus understandable that in the turbulent flow with bed form structures, the ejection is quite dominant in the crest of the dune, while the trough is much dominated by the sweeping event.

Fig. 4: Comparison of conditionally averaged turbulent intensity profiles over plane bed with time averaged profile over dunes; (a) streamwise turbulent intensity, (b) vertical turbulent intensity

5 Conclusion
The purpose of this study was to investigate the influence of bed forms on the main flow over a series of 2D dunes. A development of turbulent boundary layer thickness along the flow over the dune covered surface is observed, in which the flow characteristics vary up to the 25th dune. The study over a single dune in the fully developed region reveals that there is a similar behavior of time averaged flow over the dune with that with the conditionally averaged flow over plane bed. This develops an approach how coherent structures can be explained using a time averaged analysis when it is present with the bed forms. It is also found out that sweeping events are much dominant in the near wall region, where as the ejections dominates in the outer region. This work explains the impact of wavy bed roughness, which are responsible for sediment transport in rivers as well.

References: