Study of Flow Structure over the Ripples in the Bed of Open Channel

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Abstract

The structure of turbulent flow over the ripples in an open channel is very important for sediment entrainment and transport and it is a flow characteristic that is not completely understood at present. In this study, the flow structure over ripples was investigated experimentally. To investigate flow structure, the velocity of flow over the ripples in an open channel was measured in three dimensions using an Acoustic Doppler Velocity meter (Micro-ADV). The velocity of the flow was measured at 128 points in the flow with a sampling rate of 50 samples per second. The time averaged flow velocities in the longitudinal and vertical directions were computed prior to analysis of velocity fluctuations to find the contribution of the bursting events into Reynolds shear stress. Presented herein is a discussion of the contribution of bursting events and the Reynolds shear stress as determined in this paper.

Keywords: Bursting process, ripples, sediment entrainment, shear stress occurrence Probability,

1. Introduction:

The process of sediment transport is very complicated due to the interaction of many processes. Nonetheless, the importance of sediment transport is increasing due to the need for rivers to be used for satisfaction of multiple purposes. Nezu and Nakagawa (1993) showed that the turbulence intensity in open channel flow is often used as an indicator of flow characteristics to maintain sediment particles in suspended load.

The concept of the bursting phenomenon was introduced initially by Kline *et al*. (1967) as a means of describing the transfer of momentum between the turbulent and laminar regions near a boundary. Four alternative types of bursting events have been identified with each of these types having different effects on the mode and rate of sediment transport in open channel flow (Bridge and Bennett 1992). Particle entrainment from the bed is closely related to the sweep event (Thorne et al. 1989; Nelson et al. 1995; Drake et al. 1988; Keshavarzi and Ball 1997, 1999). In turbulent flow, the bursting process is the major process for momentum transfer and is very effective for the entrainment and subsequent transport of sediment particles from the bed and at the bed. The contribution of sweep and ejection events has been found to be more important than outward and inward interactions for this purpose (Nakagawa and Nezu 1978; Grass 1971). Furthermore, sweep and ejection

events occur more frequently than outward and inward interactions (Nakagawa and Nezu 1978; Thorne et al. 1989; Keshavarzi and Ball 1997) with the average magnitude of the shear stress during a sweep event being much higher than the time averaged shear stress (Keshavarzi and Ball 1997). A number of studies, for example Offen and Kline (1975) and Papanicolaou *et al*. (2002) investigated the characteristics of the bursting process and its effect on particle motion. Consideration of this research led Yen (2002) to point out the necessity to incorporate the bursting process into the modelling of turbulent flow and sediment transport.

Cardoso *et al*. (1991) studied gradually accelerating flows in a smooth channel using a one-component hot-wire anemometer. They also measured the bed-shear stress directly by using a skin friction probe and found that the bed-shear stress increased along the stream-wise direction. Sajjadi *et al*. (1996) found that the vortices that form in the lee of ripples in an oscillatory flow are important for the entraining of sediment.

The present research is thus a further contribution to our understanding of the flow structure in rough non-uniform flow. The condition for which a nonuniform flow is in equilibrium is discussed in detail. A 3D ADV is employed to measure the flow and turbulence velocity fluctuations over the ripples at different sections along the streamwise direction of an open channel.

2. Experimental method

The experiments were carried out in a non-recirculating glass flume located in the hydraulics laboratory at Shiraz University. The glass flume consisted of a rectangular cross-section with base width of 0.70m, height 0.60m and 15.50m length. The longitudinal slope of the flume was set to 0.0005. The flow rate at the end of the flume was measured using a pre-calibrated 90^{o} V-notch weir. A downstream adjustable gate was installed at the downstream end of the flume to allow for adjustment of the flow depth and velocity within the flume.

In the study reported herein, experimental measurements were made for three different forms of ripples; the wave lengths of the ripples considered were 15, 20 and 25cm while the height of the ripples were 3cm for all wave lengths. The flume bottom was covered with an erodible bed material layer consisting of sand particles with mean average size (d50) of 0.62mm. A schematic of the ripple dimensions considered is shown in Figure 1.

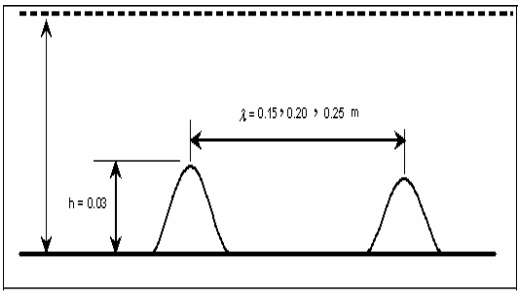


Fig 1-Ripple geometry used in this study

The experimental tests were performed with the flow conditions noted in Table 1. As indicated in that table, the flow rate for these tests was approximately 18.5 litres per second and the flow depth was constant at 14.5cm. The flow velocity was measured in three dimensions using an Acoustic Doppler Velocity meter (Micro-ADV) at the points within the flow. The measurements were made at eight depths within the flow; these depths were 0.5, 1, 1.5, 2, 2.5, 3, 5 and 6cm from the bed and at 16 longitudinal sections along the flume.

Table 1: Experimental flow conditions

Test Number	Flow rate (l/s)	Flow depth (cm)	Froude number	Reynolds number
Run 1	18.48	14.5	0.153	26400
Run 2	18.50	14.6	0.151	26428
Run 3	18.52	14.3	0.156	26457

3. Results and discussion

The bursting process consists of four categories of event; these categories are defined by the quadrant analysis of the event. As shown in Figure 2, the events are:

- sweep $u'>0, v'<0$; ejection $u'<0, v'>0$; outward interaction $u'>0, v'>0$; and inward interaction $u'<0, v'<0$. T

The velocity fluctuations v' و u' are defined as variations from the temporal mean velocities in the longitudinal and vertical directions, respectively. Algebraically, they are defined by equation 1 as described below;

$$u' = u - \bar{u} \text{ and } v' = v - \bar{v} \qquad (1)$$

Where

$$\bar{u} = \frac{1}{n}\sum_{i=1}^{n} u_i \text{ and } \bar{v} = \frac{1}{n}\sum_{i=1}^{n} v_i \qquad (2)$$

and n is the number of instantaneous velocity samples.

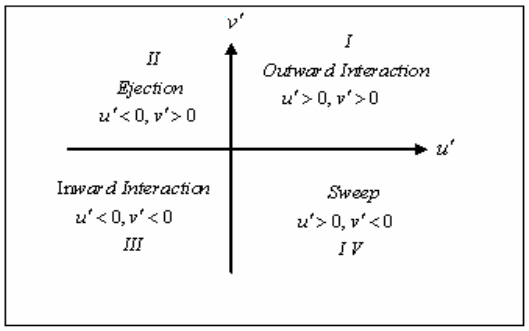


Fig 2- Four classes of bursting events and their associated quadrants

The contributions of coherent structures, such as the sweep (Quadrant 4) and ejection (Quadrant 2) events, to momentum transfer have been extensively studied through quadrant analyses of two-dimensional velocity fluctuations. Using similar techniques, the contributions of the four events to the entrainment and motion of sediment particles were determined from the experimental measurements. Shown in Figures 3 to 6 are the frequencies of bursting events along the flume. From a quadrant analysis of velocity fluctuations, it was found that at a level of 0.5cm from the bed downstream of the second ripple, Quadrants 1 and 3 were dominant when compared to Quadrants 2 and 4. This can be interpreted as an expectation that sedimentation should occur at this location. However, upstream of the ripple, Quadrants 2 and 4 were dominant to Quadrants 1 and 3. Therefore entrainment would be expected to occur at this location. These expectations are confirmed by measuring the bed profile over the ripples along the bed.

The magnitude of the mean instantaneous shear stress for each quadrant was found to be different, and to differ from the overall temporal mean shear stress for the flow. The instantaneous shear stress for each event was normalized by the total mean shear stress at that point within the flow. Expressed algebraically, the non-dimensional instantaneous shear stress was determined by

$$C = \frac{\tau'}{\bar{\tau}} \qquad (3)$$

where τ' is the instantaneous shear stress and $\bar{\tau}$ is the time averaged n shear stress at that point in the flow. In order to transform the normalized data into a normally distributed data, a Box-Cox

power transformation (see Box and Cox, 1964) was used to transform the original data denoted by the symbol C to the transformed data denoted by B(C).

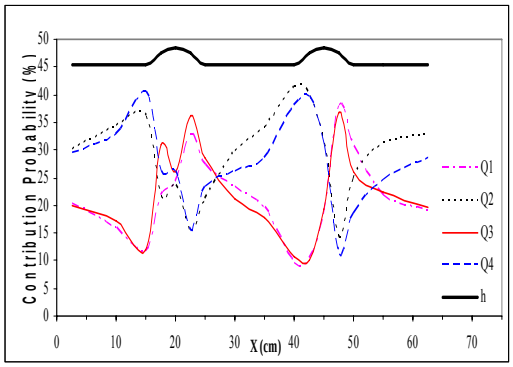


Fig 3- Bursting events at 0.5 cm from the bed

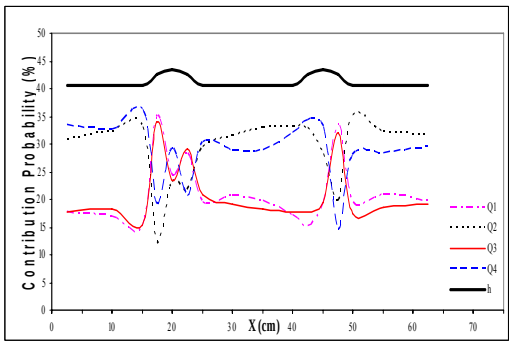


Fig 4- Bursting events at 1 cm from the bed

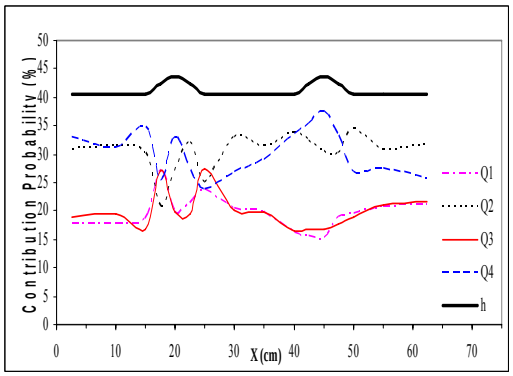


Fig 5- Bursting events at 1.5 cm from the bed

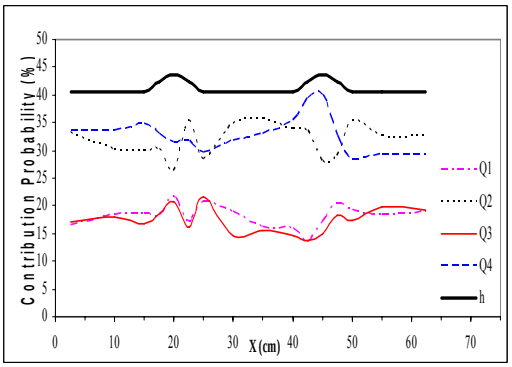


Fig 6- Bursting events at 2 cm from the bed

The shear stress distributions of the bursting events were calculated and the variations of shear stress over the ripples and along the length of flume are shown in Figure 7.

4. Conclusions

In this study the flow structure over the ripples was investigated experimentally. Consideration of these results showed that, upstream of the first ripple, bursting events in Quadrants 2 and 4 are dominant; also it was found that the maximum entrainment of sediment particles occurred upstream of the ripple. However, downstream of the ripple, the bursting events in Quadrants 1 and 3 are dominant and that sediment deposition occurred downstream of the ripple. Additionally, consideration of the results showed that, as the distance between the ripples decreases, the entrainment and deposition zones increase. Also, consideration of the results for different depths within the flow showed that the non dimensional shear stresses of quadrants are fluctuating along the ripple.

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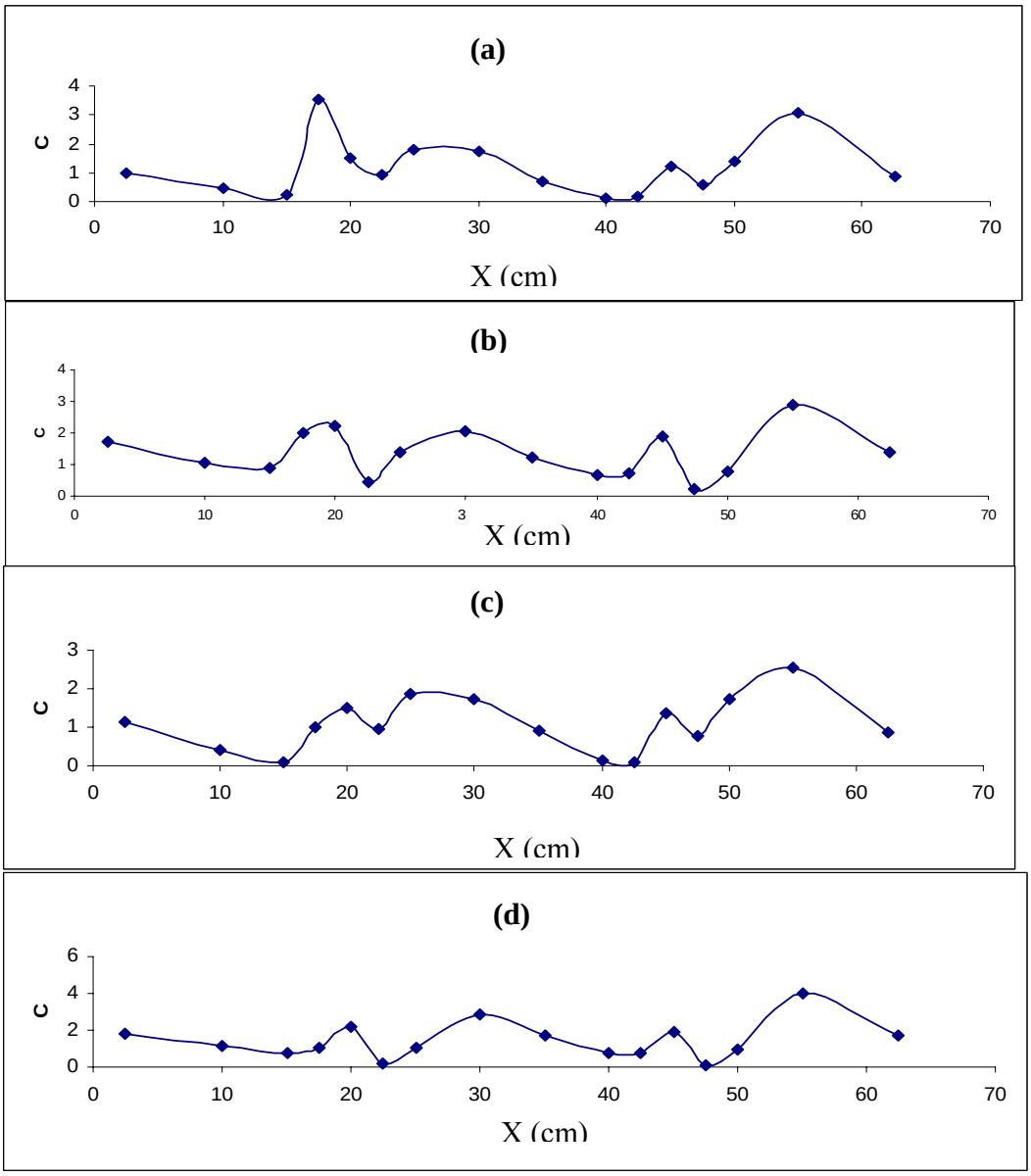


Figure 7- Distribution of non dimensional shear stresses in the length of flume at 0.5 cm from the bed: a) Outward interaction, b) Ejection, c) Inward interaction, d) Sweep