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Study of instantaneous flow behind a single fixed ripple

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ABSTRACT

Two-component velocity measurement using Particle Image Velocimetry (PIV) and flow visualizations have been performed to investigate the different hydrodynamic mechanisms process over a fixed single ripple. Flow patterns over ripple are studied for five Reynolds number based on ripple height ($Re = 125$, 300, 500, 600 and 700). Results show that the unsteady flow is reflected in vortex pattern generation over the ripple. While for $Re < 500$, a recirculation zone and a longer length of reattachment point are observed. When $Re > 500$, instantaneous flow visualization shows an intense vortex interaction with or without coalescence associated with a decrease of the length of the reattachment point. Furthermore, quadrant decomposition of the instantaneous Reynolds shear stress has been calculated to analyse the contribution of the four events in shear stress generation. In addition of a spatial cycle dominance of the sweeping and ejection events near bed, inward interaction events seem to contribute also to this cyclic process and to the flow features.

1. Introduction

The intermittency of the flow in rivers leads to the formation of ripple, dune, antidune forms. These forms are the result of a combination between high scouring and deposition processes at riverbeds. This complex process controls the sediment concentration, bed forms shape and slope of channels. The dynamics of these patterns depends on the interaction between turbulent flow and particles. Even though the sediment transport is largely documented (Shields, 1936; Vanoni, 1964), the relationships between the flow characteristics and forces acting on sediments remains unknown (Gyr and Hoyer, 2006). Therefore, a better understanding of the flow turbulence characteristics near bed can give a better view of the origin of this interaction and its influence on sediment transport. The occurrence of these patterns has been studied in order to identify the behaviour of alluvial channel (Bagnold, 1941; Richards, 1980; Engelund and Freds¢e, 1982; Kadota and Nezu, 1999; Blondeaux, 2001; Best, 2005; Seminara, 2010; Charru et al., 2013) or the flow features over sediment patterns (Kadota and Nezu, 1999; Hyun et al., 2003; Stoesser et al., 2008).

Since flow separation over backward-facing step is largely similar to that over ripples, various experimental and numerical studies with backward-facing step were conducted to better understand ripple formation (i.e. Raudkivi, 1963; Nagakawa and Nezu, 1987, 1977; Silveira et al., 1993). However, topography difference between negative step and ripple induced a modification of turbulent structures due to the presence of the stoss slope and the angle of the lee side (Paarlberg et al., 2007; Nelson et al., 1993). Therefore, laboratory experiments (Jackson and Hunt, 1975; Best, 1992; Kadota and Nezu, 1999; Hyun et al., 2003; Charru et al., 2013), numerical studies (Scandura et al., 2000; Stoesser et al., 2008; Xie et al., 2013) and empirical models (Nelson and Smith, 1989; Charru and Hinch, 2006) were carried out under such conditions, that can accurately give physical characteristics of the active process over ripples and dunes.

The effect of flow topology on the sediment transport is largely studied over subaqueous bedforms (Müller and Gyr, 1986; Bennett and Best, 1995; Venditti and Bennett, 2000; Coleman and Nikora, 2009; Shugar et al., 2010), but for ripples a few attempts have been made (Ha and Chough, 2003; Coleman and Nikora, 2011). Raudkivi (1963) noted that near the reattachment point, sediment particles are moved by turbulence, wherein the flow separation generates high instantaneous bed shear stresses which causes erosion of grains (Bennett and Best, 1995). As a consequence, the boundary shear stress increases due to flow reattachment, flow acceleration and turbulence (Raudkivi, 1963). Hence, the fluid forces acting upon sediment vary and scale the nature of the interaction between flow fluctuations and available grains, resulting in bedload and suspension sediment transport.

The investigation of flow fluctuations structures is conducted on the variation of the Reynolds shear stress, which is described by a quadrant method analysis. This analysis is considered to be important for describing sediment transport. Four types of quadrants have been identified by Lu and Willmarth (1973) and each one has a different effect on the mode and rate of sediment transport (Bridge and Bennett, 1992). Most of the studies show the implication of quadrants on the sediment motion (i.e. Grass, 1971; Heathershaw and Thorne, 1985; Nelson et al.,

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1995; Papanicolaou et al., 2002; Keshavarzi et al., 2012). Since the sediment is moved by forces resulting from turbulent fluctuations, this analysis seems to be interesting to describe all the active process which can lead to grains motion. Recently, few studies focused on the importance of sediment patterns interaction with the instantaneous flow using experiments (Kadota and Nezu, 1999; Hyun et al., 2003; Coleman et al., 2006) and simulations (Stoesser et al., 2008). The focus of these studies is different but the description of the flow is limited almost on mean characteristics of different quantities and global instantaneous flow field. Therefore, the present contribution highlights the evolution of the instantaneous flow fields and the spatio-temporal behaviour of multiple-scales vortices over a single fixed ripple.

The present study uses optical measurements technique such as two-components Particles Image Velocimetry (PIV) and visualization technique to highlight the flow structures behind a fixed ripple with a bed form stoss slope. Measurements and analysis of different flow structures for several Reynolds numbers over a single fixed ripple on bound flow are conducted. Firstly, mean flow characteristics have been calculated for two components (velocity amplitude, Reynolds shear stress, vorticity, turbulent intensity). Measurements show a presence of flow separation at the ripple crest leading to the formation of a recirculation zone on the leeside of the ripple. Secondly, instantaneous flow patterns are discussed in details for various Reynolds numbers. Finally, the vortex shedding phenomenon is highlighted and discussed using spectral analysis and instantaneous flow capture.

2. Experimental set up

2.1. Ripple and flume

The study is carried out using a fixed ripple with 20 mm height (i.e. Wiberg and Nelson, 1992; Kadota and Nezu, 1999; Hyun et al., 2003; Yue et al., 2006; Stoesser et al., 2008). The ripple shape adopted in this study is shown in Fig. 1-a, and is determined by a trigonometric function detailed in Kadota and Nezu (1999).

The experimental device is a closed loop horizontal water channel (Fig. 1-b). The test section is a square plexiglass duct of 16 × 16 cm. Cartesian coordinate system is used to represent the results R (O/X, Y, Z). The origin O is localized on the symmetry plane of the ripple, down the vertical crest. The X, Y and Z axis are set in the longitudinal, spanwise and upward directions respectively. Tests are performed for five Reynolds numbers based on the ripple height, $Re = Uh/\nu$, where U is the inlet velocity, h is the ripple height and ν is the fluid kinematic viscosity. The Reynolds number tested are: 125, 300, 500, 600 and 700 which correspond to flow speed: 0.0062, 0.015, 0.025, 0.03 and 0.035 m/s, respectively. The flow quantities are presented in the dimensionless form and are normalized by the inlet velocity (U), whereas the coordinate system is normalized by the ripple height (h).

2.2. Measurement techniques and flow conditions

Flow visualization technique and two-component velocity measurements by Particle Image Velocimetry (2C-2D PIV) are performed to quantify the unsteadiness characteristics of the fluid motions. The visualization technique consists of recording instantaneous images of flow, using a light sheet that illuminates particles within the flow (particles are consider as a tracers that move with the local flow). For the PIV technique, the measurement system consists of one CCD camera and Nd-Yag laser. The flow is seeded by hollow glass particles (12 µm diameter) and then is illuminated with a double pulse Nd-Yag laser, with a wavelength of 532 nm. The laser sheet illuminates the flow in a plane parallel to the channel bed of the ripple. In order to record velocity fields, a camera with a high spatial resolution of 1200 × 1600 pixels is used (Fig. 1-b). The Dantec software «Dynamique Studio» computes multi-passes cross-correlation analysis on successive images using windows area size ranging from 128 × 128 pixels to 16 × 16 pixels with 50% overlap. Consequently, two sets of 4096 and 1024 instantaneous velocity fields are acquired with a frequency rate ranging from (4, 8, 10, 14, 14 Hz), corresponding to Reynolds number (125, 300, 500, 600, and 700), respectively. In order to obtain time mean values of velocity components and turbulence statistics, results are averaged over 4096 data sets for all Reynolds numbers except Re = 125 which is averaged over 1024 data sets.

3. Methods for predicting sediment transport from PIV measurements

3.1. Quadrant method

The PIV provided the streamwise and the vertical components of the instantaneous velocities, (u and$w$), respectively. The velocity fluctuations u' and w' are defined as variation from time-average velocities [Eq. (1)]:

$$u' = u - \bar{u} \quad \text{and} \quad w' = w - \bar{w}; \tag{1}$$

where the mean velocity of flow field is calculated from:

$$\bar{u} = (1/n)\sum_{i=1}^{n} u_i^n \quad \text{and} \quad \bar{w} = (1/n)\sum_{i=1}^{n} w_i^n \tag{2}$$

where u_i^n and w_i^n are the i-th realization of the streamwise and upward velocity components.

The Quadrant method is used to characterize the flow downstream

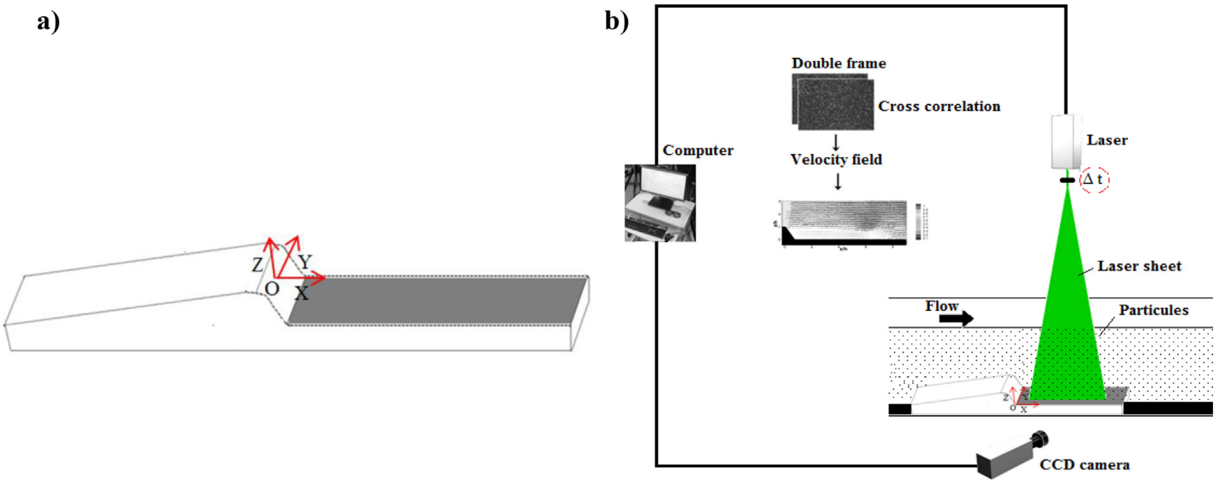

Fig. 1. a) Ripple coordinates system b) Schematic sketch of PIV system.