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Spatially-averaged turbulent flow over cubical roughness in wave-current co-existing environment

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ABSTRACT

The paper describes an experimental study carried out in a laboratory flume to investigate the interaction of surface-wave with unidirectional current over cube mounted rough-bed (3D flow). The cubes were made of wood and were positioned at the channel-bed with different spacing. The spacing was chosen to represent different roughness types under different spacing conditions as: isolated roughness flow, wake interference flow and skimming flow. The three-dimensional velocity field was measured by an acoustic Doppler velocimetre (ADV). The study particularly focused on the changes induced in the spatially-averaged velocity profiles, turbulence intensities and Reynolds shear stress due to the superposition of waves of different frequencies on current-induced flow. Spatially-averaged velocity profiles show two distinct distributions: linear or exponential distribution below the roughness crest and logarithmic distribution above the roughness crest. It is found that the shift of the velocity profile depends strongly on the spacing of roughness elements. The profile of stream-wise turbulence intensity changes significantly below the roughness crest due to presence of surface wave, whereas bottom-normal spatially-averaged turbulence intensity does not change much with increase in wave frequency. Within the roughness crest near the bottom, the form-induced shear stress changes significantly from negative to positive value with change in roughness spacing, but is not affected much due to the presence of surface-wave.

1. Introduction

Flows observed in coastal environments are usually a combination of waves and currents. The combined wave-current flows govern many physical processes of interest to oceanographers and engineers working in coastal environments. In coastal and estuarine regions, wave and current coexist and create an effective environment for sediment transportation. The influence of wave motion on the bed causes significant quantities of sediment to be suspended above the bed, and it is then transported with the horizontal component of the flow velocity. It has been a subject of great interest to many researchers due to its immense practical significance.

In order to understand the physical phenomena arising from the combined wave-current flows, several investigations had been carried out over the last few decades theoretically as well as experimentally over the rough-bed surface (Grant and Madsen, 1979; Brevik and Aas, 1980; Christofferson and Jonsson, 1985; Sleath, 1991; Nielsen and You, 1996; Mathisen and Madsen, 1996a,b; Mazumder and Ojha, 2007; Ojha and Mazumder, 2010 and others). A time invariant one-layer eddy viscosity model was developed by Grant and Madsen (1979) to describe the combined wave-current flows in the vicinity of a rough boundary, predicting an apparent increase in bed roughness and shear stress. Brevik and Aas (1980) reported results of both following and opposing currents with surface waves over ripple beds to study the mean velocity and friction factor. Subsequently, Brevik (1980) conducted similar experiment, replacing the ripple-bed with a smooth-bottom. On the other hand, Brevik (1981) and later Myrhaug (1982) extended the one-layer eddy viscosity model proposed by Grant and Madsen (1979) to a two-layer time invariant model and developed analytical solution for the velocity profiles in the rough boundary layer.

Kemp and Simons (1982) reported an experimental study for wave-current interaction over smooth and rough boundaries, with waves propagating along the current; and a considerable increase in bed shear stress was observed at the rough boundary. Subsequently, Kemp and Simons (1983) studied combined wave-current driven flow, with waves propagating against the current over the smooth and rough beds for comparison of the results with those observed with the waves following the current. They observed that the near-bed velocities for rough-bed were reduced, while near-bed turbulence intensities for both rough and smooth surfaces were increased by the presence of surface waves. Similar results were obtained by Klopman (1994) experimentally in a laboratory flume over a rough-bed. Nielsen and You (1996) presented two-dimensional (2D) wave-current interaction model, which was only applicable to the weak current. However, they

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also proposed that the agreement of the model for stronger current could be obtained by modifying the wave Reynolds stress to account the influence of the current on the wave motion. Mathisen and Madsen (1996a,b) presented experimental studies on combined wave-current flows over fixed rippled-bed to characterise the bottom roughness for wave and current boundary layers. They focused on the apparent hydraulic roughness in the case of the combined flow and showed that the apparent hydraulic roughness was underestimated, as was proposed by Grant and Madsen (1979). Fredsoe et al. (1999) conducted experimental as well as numerical study of combined wave-current flow over symmetric ripple-covered bed. A detailed description of turbulent structure throughout the depth of flow is provided by Umeyama (2005) based on experiments in a laboratory flume over a smooth-bed for a wave-current flow with different wave-heights and wave-periods. Recently Ojha and Mazumder (2010) reported the results of the experimental study of mean flow and turbulence over a series of two-dimensional (2D) bed forms in the presence of surface-waves of different frequencies. They showed that the effect of surface-waves increased the flow stability, consequently reduced the flow separation and enhanced the mixing in the lee-side of the bed form.

Numerical models based on Navier–Stokes equations have been developed to analyze the combined wave-current flows over rough-surface (Johnson et al., 2005; Zheng and Tang, 2009; Zhang et al., 2011 and others). Teles et al. (2013) applied a CFD solver based on Reynolds-Averaged Navier–Stokes (RANS) equations to model the combined wave-current flow at a local scale with a second-order piston-type wave boundary condition at one end of the channel for the wave simulation. Recently, Zhang et al. (2014) applied RANS equations with k-epsilon turbulence closure scheme. Their numerical simulations agree well with the experimental observations.

However, the time-averaged flow structure is highly three dimensional (3D) and spatially heterogeneous at the near rough-bed region. To address this spatial flow heterogeneity in the near-bed region, the double-averaged Navier–Stokes equations were suggested as an appropriate theoretical frame-work. The concept of spatially-averaged methodology over a wavy-bed in the field was first introduced by Smith and McLean (1977). This concept was used to reduce the errors substantially due to the non-uniformity of flow over the wavy-beds. Subsequently, Wilson and Shaw (1977) developed a methodology based on the spatially-averaged equations to study atmospheric flows within vegetation canopies. In the later stage, Raupach and Shaw (1982), Finnigan (1985), Raupach et al. (1991) provided a mathematical basis for a new set of equations for the atmospheric flows. The similar mathematical approach was successfully used by Gimenez-Curto and Corniero Lera (1996) to describe the oscillatory turbulent flows over very rough-surface. Nikora et al. (2001) used the double-averaged momentum equations to study the hydraulics of rough-bed in open-channel flows with small relative submergence. The double-averaged methodology was used to smooth the spatial variability of time-averaged flow induced by roughness elements and to determine the form-induced momentum fluxes due to spatially heterogeneity of the time-averaged flow. However, the use of double-averaging methodology required large amount of data in the near-bed region. In some conditions, this requirement may impose a grievous restriction on the use of double-averaging methodology (Nikora et al., 2007).

Relatively a little attention has been given to study experimentally the combined wave-current driven flow concerning the turbulence statistics over a regular rough-bed, despite the fact that such study has a great importance in practice. Here the term 'regular rough-bed' is different from a rough boundary (flat rough surface) in the sense that the bed is covered with relatively large, regular roughness elements; and as a result, regular, large-size vortices are routed into the flow stream in a classified manner (both in space and in time). The main objective of the present paper is to investigate experimentally the effect of the superposition of surface-waves of different frequencies on the unidirectional flow over the artificial cube mounted rough-bed surface using double-averaging technique. More precisely, an attempt has been made to study the effect of roughness spacing on the double-averaged turbulence parameters like mean velocity, turbulence intensities, Reynolds shear stress and form-induced shear stress due to surface-waves of different frequencies on the flow over rough-bed. The investigators are affirmative that the quantitative knowledge generated in the present study will be useful for numerical modeling or laboratory investigations of hydraulics of rough-bed flows, and in understanding sediment pickup, grain-sorting and transportation under coastal environment in the rough-bed dominated regions.

2. Theoretical background

In turbulent flow, if u, v, and w represent the instantaneous stream-wise, lateral and bottom-normal velocity components in the x, y, and z directions respectively, the following three relations can be written:

$$u=\overline{u}+u', \qquad v=\overline{v}+v', \qquad w=\overline{w}+w' \tag{1}$$

where $\overline{u},\overline{v}$ and $\overline{w}$ are the time-averaged velocity components and u',v' and w' are the corresponding velocity fluctuations. The time-averaged stream-wise and bottom-normal velocities $(\overline{u},\overline{w})$ and the root-mean-square velocity components (σ_u,σ_w) are defined as follows:

$$\overline{u}=\frac{1}{N}\sum_{i=1}^{N}u_i \tag{2}$$

$$\overline{w}=\frac{1}{N}\sum_{i=1}^{N}w_i \tag{3}$$

$$\sigma_u=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(u_i-\overline{u})^2} \tag{4}$$

$$\sigma_w=\sqrt{\frac{1}{N}\sum_{i=1}^{N}(w_i-\overline{w})^2}. \tag{5}$$

Further the time-averaged Reynolds shear stress (τ) at each measuring point is obtained as follows:

$$\tau=-\rho\overline{u'w'}=-\rho\frac{1}{N}\sum_{i=1}^{N}(u_i-\overline{u})(w_i-\overline{w}) \tag{6}$$

where $N=$ total number of observation at each measuring point; and $\rho=$ density of the fluid. It may be noted here that in the present study, the instantaneous velocity data were collected continuously for 3 min, 4 min and 5 min duration at the same measurement point for the testing purpose. These test measurement points were chosen both above and below the roughness top; and the time-averaged statistics of velocity data for each duration of time gave almost same mean and variance. Therefore, in the present experiment the sampling time was chosen equal to three minutes to satisfy the ergodicity condition, with reference to the velocity mean and variance (Bendat and Piersol, 2000).

When waves are combined with a current, it is important to introduce phase-averaged quantities, because the turbulence properties in the combined velocity signal due to the wave component are changed. In the combined wave-current flow, the instantaneous velocity can further be expressed as (Nielsen, 1992; Umeyama, 2005; Singh et al., 2015):

$$u=\overline{u}+\hat{u}+u' \tag{7}$$