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Wave-current generated turbulence over hemisphere bottom roughness

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ABSTRACT

The present paper explores the effect of wave-current interaction on the turbulence characteristics and the distribution of eddy structure over artificially crammed rough bed prepared with hemispheres. The effect of the surface wave on temporal and spatial-averaged mean velocity, intensity, Reynolds shear stress over, within cavity and above the hemispherical bed are discussed. Detailed three-dimensional time series velocity components were measured in a tilting flume using 3-D Micro-Acoustic Doppler Velocimeter (ADV) at a Reynolds number, 62×10^3. This study reports the fractional contributions of burst-sweep cycles dominating the total shear stress near hemispherical rough surface both for current only flow as well as for wave-induced cases. Wavelet analysis of the fluctuating velocity signal shows that the superimposed wave of frequency 1 Hz is capable of modulating the energy containing a range of velocity fluctuations at the mid-depth of the cavity region (formed due to the crammed arrangement of the hemispheres). As a result, the large-scale eddies (with large values of wavelet coefficients) are concentrated at a pseudo-frequency which is equal to the wave oscillating frequency. On the other hand, it is observed that the higher wave frequency (2 Hz) is incapable of modulating the eddy structures at that particular region.

1. Introduction

Natural marine, continental shelf and coastal environments such as the beach, surf zone, middle and lower shoreface are dominated by breaking waves, wave induced currents and tidal waves. Thus, study and analysis of this combined wave-current interaction are of great importance for improved management of coastal zone and in particular quantification in particular of the seabed, pipeline scours, bank erosion management, quantification of the spread of pollutants and in understanding nearshore biological processes influenced by wave interactions. The mechanics of the interaction of combined wave-current flow over and within a crammed bottom roughness is complex and results in perturbation of the turbulence field resulting in changes in the eddy-scale distribution of energy (Roy et al., 2017); modified flow resistance, bursting structure of turbulence and also the spectral character of velocity fluctuations.

An ongoing effort is being made to gain a better understanding of the mechanics and flow characteristics of combined wave-current interactions on the smooth and sediment-laden bed over the last three decade. These studies were based on flume measurements for the characterization of mean velocity and second order moments of velocity under wave-current interactions with waves following the current for the flat surface (e.g., Van Hoften and Karaki, 1976; Kemp and Simons, 1982; Umeyama, 2005, 2009) and also for rough-bed (e.g., Sleath, 1987; Van Rijn and Havinga, 1995; Fredsoe et al., 1999; Marin, 1999; Dumas et al., 2005). Similarly, a number of numerical and analytical investigations are found in the literature on the wave-current interaction problem (Grant and Madsen, 1979; Hsu et al., 2009; Wen et al., 2012; Teles et al., 2013; Zhang et al., 2014, 2015). Brevik and Aas (1980) and Van Rijn and Havinga (1995) generated waves following current over the sediment beds to study the mean velocity and friction factor changes under wave induced conditions. Series of velocity measurements were taken for turbulent oscillatory flow over different rough bed such as the single layer of sand, gravel or pebble (Sleath, 1987). Results showed that close to the roughness, the turbulence reached its maximum intensity and Reynolds shear stress due to velocity deceleration. The velocity and

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turbulence statistics due to wave-current interaction over a ripple-covered bottom wall was studied both experimentally as well as numerically by Fredsoe et al. (1999). Umeyama (2005, 2009) performed a series of experiments in an open channel flow under wave-current interaction. It was reported that the Reynolds stress profile changed for the combined wave-current environment. The superimposition of waves caused a reduction of turbulence stresses not only near the bottom but also throughout the water depth. A Eulerian wave-current model was reported by Olabarrieta et al. (2010) in order to analyze the effect of wave-current interaction on the mean steady current profile. They pointed out that the effect of wave-current interaction is not restricted only to the bottom wave boundary layer region but to the entire water depth. Zhang et al. (2014) proposed a numerical model to study the wave propagation in the presence of steady current flow using a CFD solver based on RANS equations.

Turbulent flow over roughened bottom wall is an important topic to researchers in different disciplines, such as hydraulics, geophysics, applied mathematics, environmental and earth science. Also, in the vast majority of atmospheric and environmental flows, the ground surface is in general hydraulically rough. Therefore, a clear understanding of such flows over the hydraulically rough bed is needed for accurate modeling of sediment entrainment and coastal protection. Towards this, many experimental and numerical simulations (Grass, 1971; Raupach et al., 1991; Dancey et al., 2000; Singh et al., 2007; Bomminayuni and Stoesser, 2011) have been carried out to comprehend the flow characteristics in the vicinity of roughened bottom surface. Grass et al. (1991) investigated the span-wise structure of the near-wall turbulence using the hydrogen bubble tracer technique. Their results demonstrated that the span-wise flow structure adjacent to a rough boundary exhibit the cross-flow wavelength, which is directly proportional to the size of the wall roughness elements. An existence of hierarchies of vortices with a characteristics length scale, turbulent coherent structures, and longitudinal streaks was reported to be clearly visible just at the top of the roughness elements (Defina, 1996). Also, Manes et al. (2007) reported mean velocities, intensities, Reynolds shear stress and form-induced normal and shear stresses over a rough surface covered by 12 mm diameter spheres based on experimental work using PIV. Singh et al. (2007) identified streaky nature of the flow near the effective wall and reported the existence of a hierarchy of vortices along the stream-wise direction using the numerical simulation of rough bed turbulent flow. Similarly, Bomminayuni and Stoesser (2011) carried out large-eddy simulation (LES) of turbulent flow over channel bed roughened by hemispheres. They concluded that the time-averaged mean velocity and higher order turbulence statistics are greatly perturbed near the wall due to bottom roughness.

In the present study wavelet analysis of the turbulent velocity signal was performed to provide insight into the structure of eddies generated due to bottom roughness for wave-current flow interaction. Wavelet transform has been used to analyze the turbulent random signal in many studies on turbulence field (e.g., Farge, 1992; Szilagyia et al., 1999; Niu and Sivakumar, 2013; Wang et al., 2016; Roy et al., 2017). In order to understand the behavior of eddy structure of turbulence, continuous wavelet transform was carried out on the turbulent velocity signal Farge (1992). Further discrete orthonormal wavelet transformation was applied to turbulence measurements for identifying coherent structure (Szilagyia et al., 1999). Wang et al. (2016) stated that the wavelet analysis of random signals is capable of providing information on the eddy scale and their associated occurrence frequency. Further, based on wavelet analysis of random velocity signal for wave-current interacting flow, it was reported that the length scale of eddies was modified significantly due to the superimposition of the wave on only current flow (Roy et al., 2017).

In spite of all these studies mentioned above, only a few experimental studies were performed to simulate the turbulent structure over rough bed under wave-current interacting environment. The objective of the present study is to provide an improved understanding of the mean and the fluctuating flow fields and the associated coherent structures over a fully submerged rough hemisphere bottom. More precisely, due to the superimposition of the surface waves on the flow over these submerged obstacles, the deviations of mean velocity, turbulence intensities, Reynolds shear stress are investigated. This study also presents probability density distribution of the random turbulent signal to gain understanding of the oscillation patterns. Further wavelet transform of the random velocity signal is reported in the context of quantifying the eddy distribution for the modulated turbulence characteristics under the complex interaction between current, waves and the rough bed. Thus the results of the present investigation will provide an improved understanding the turbulence characteristics in a wave-current interacting boundary layer, which in turn will aid in providing insight into the different physiological processes associated with marine flora and fauna in the marine environment.

2. Methods

2.1. Experimental arrangement

Experiments were conducted in a laboratory flume at the Fluid Mechanics and Hydraulic Laboratory (FMHL) of the Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India. A specially designed flat-bed open-channel flume of dimension 18.3 m long, 0.90 m wide and 0.90 m deep with a constant slope of 0.00025 was used for the experiments. The test section was located 11 m from the upstream end of the flume, where transparent Perspex sidewalls of the flume facilitated to observe the flow. To ensure a smooth condition for the entrance of flow 4 perforated baffle walls are used at the inlet tank for breaking the large-scale turbulent structures. The discharge valve was gradually opened to achieve desired discharge and an adjustable tailgate was kept at the downstream end of the flume to control the flow depth. The wave absorber (made of 0.9 m length 0.2 m width and height 0.15 m sponge block) was located at the downstream of the flume to absorb the wave energy (reflected from the tail gate). Please note that the discharge of the flume was overflow type, thus most of the wave energy was released due to overflow from the outlet. However to minimized the wave reflection from the down-stream side, the sponge block was used. A plunger-type wave maker was installed at the upstream end of the flume to generate surface waves (Fig. 1a).

2.2. Experimental conditions and procedures

A SonTek down-looking 16 MHz micro-acoustic Doppler velocimeter (Micro-ADV) was mounted on the flume to measure the fluid velocity with fluctuations over the rib roughness. The instantaneous velocity data were recorded using ADV at 40 Hz sampling rate for 180 s at each measurement point starting from the lowest level at 0.4 cm from the bottom roughness up to 6 cm below the mean free surface level for all cases viz current only flow (COF) and combined wave-current flow having surface wave frequencies $f = 1$ Hz (WIF1) and 2 Hz (WIF2) cases. The sampling volume is nearly cylindrical shaped and oriented along the transmitter beam axis. It has a diameter equal to 0.6 cm and height 0.32 cm (SonTek Inc., 2001). The size of the sampling volume for the 16 MHz ADV is 0.09 cm^3. Factory calibration of the ADV is specified