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Turbulence between two inline hemispherical obstacles under wave–current interactions

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ABSTRACT

This paper reports an experimental investigation of open channel turbulent flow between two inline surface mounted hemispherical obstacles in tandem arrangement. A series of experiments are performed under combined wave–current interaction with seven relative spacing L/h, where L is center to center spacing distance and h is the obstacle height for Reynolds number $R_e = 5.88 \times 10^4$. The observations are particularly focused on the changes induced in the mean velocity components, turbulence intensities and Reynolds shear stress due to superposition of surface waves on the ambient flow, and are compared to that of flat-surface and a single hemisphere. The paper also investigates the dominant turbulent bursting events that contribute to the Reynolds shear stress for different relative depth influenced by hemispheres. It is observed that the contributions to the total shear stress due to ejection and sweep are dominant at the wake region for single and double hemisphere near the bed, while towards the surface outward and inward interactions show significant effect for wave–current interactions which is largely different from that over the flat-surface case. Spectral analysis of the observed velocity fluctuations reveals the existence of two distinct power law scaling regime near the bed. At high frequency, an inertial sub-range of turbulence with −5/3 Kolmogorov scaling is observed for the flat-surface. The spectral slope is calculated to show the shifting of standard Kolmogorov scale for both only current and wave-induced tests.

1. Introduction

Coastal environments, which include estuaries, tidal flats, delta fronts, etc., are characterized by distinct physical processes where different temporal and spatial scales interact e.g., waves, large scales circulation currents, tidal effects, wind action, etc. This leads to a complex turbulent flow structure which still remains largely unexplored. Understanding the mechanics of the coexisting waves and currents in the coastal zone is important for determining mass and sediment transport rates because the sediment is picked up by the waves and transported by the mean flow. The wave–current interaction provides fundamental insight into design of coastal protection, harbor sheltering structures, evaluation of sediment transport, coastal erosion rates and many others.

The flow behind the 3-D bluff bodies mounted on the surface is of fundamental importance in science and engineering. Many investigators [2,3,23,27,28,47 and others] demonstrated that the presence of obstacle in the flow field perturbs the mean flow and turbulence characteristics greatly. Further, the flow around the bluff body is characterized with highly turbulent re-circulation and wake region. Wakes behind obstacles/bluff bodies are of major interest to the fluid dynamists. A description of turbulent structure behind bluff bodies was focused by Shamloo et al. [51]. Their study was focused on the flow visualizations over the two Styrofoam hemispheres, whose diameters were 130 mm and 74 mm respectively. The entire flow depth was divided into four separate regions and the turbulence structure was described at each region. It was observed that the effect of the bed on the velocity profile was negligible away from the bed in the outer region, whereas close to the bed, its effects were dominant. Recently, Postacchini et al. [45] provided the comparative analysis of the sea wave dissipation induced by three different flow mechanisms. They also demonstrated a clear link between the dissipative mechanisms and the size of the obstacle "effective volume" over which dissipative processes occurred.

Miyagi et al. [34] provided the statistical analysis on wall shear stress of turbulent boundary layer in a channel flow using micro-shear stress imager. Agelinchaab and Tachie [2] used a particle image velocimetry (PIV) to investigate open channel turbulent flow over hemispherical ribs with three different relative spacing where the hemisphere diameter was 12 mm and Reynolds number was 28100. They observed that hemispherical ribs were less effective in augmenting flow resistance compared to 2-D transverse ribs. Abad and

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Garcia [1] performed experiments in a high-amplitude Kinoshita meandering channel: Implications of bend orientation on mean and turbulent flow structure. Also Catano-Lopera et al. [8] studied experimentally as well as numerically the flow structure around two partially buried objects- a short cylinder and a truncated cone on a deformed bed. Experiments were conducted in a large tilting flume with covered by a 24 m long sand pit. For each experiment, the object was placed on a flat sandy bed, the flume was filled to a water depth of 41 cm, and a steady unidirectional current was established at high Reynolds numbers. Bed forms surrounding the object modified the turbulent shear stresses considerably. Significant differences were observed between the object mounted on the flat bed and the partially buried object. In the case of flat bed, maximum shear stresses appeared close to the lateral edges of the object. Higher shear stresses were observed in the case of the short cylinder than in the truncated cone. As a result, the extent and depth of the scour is larger at equilibrium conditions for the short cylinder case.

Extensive investigations relevant to wave–current interactions were carried out over the last few decades in laboratory settings under controlled conditions [16,20,22,35,59 and others] and using numerical modeling [42,55,62 and others]. Brevik and Aas [4] generated both the following and opposing currents with waves over the ripple beds to study the mean velocity and friction factor. Experimental investigations by Kemp and Simons [19] showed that the near bed velocities over the rough bed for current alone were reduced, while near-bed turbulence (rough and smooth) intensities were increased due to the presence of waves. Similar results were obtained by Klopman [21]. Faraci and Foti [13] also studied the geometry, migration and evolution of small scale bed form structures generated by regular and irregular waves. Umeyama [57] performed a series of experiments in an open channel of 25 m length, 0.7 m wide with a water depth of 0.2 m. Regular waves were generated with a piston type wave maker. Wave height and wave period were varied in different tests. Experiments were carried out for only current, waves following current and waves against current. The mean velocity in the channel was about 12 cm/s, either in the same direction as the direction of waves or in the opposite direction. Vertical profiles of mean velocity and Reynolds shear stress were measured at a distance of 10.5 m from the wave generator. A significant reduction of the mean velocity was observed up-to mid water depth from the water surface. It was noted that the Reynolds stress profile was 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. The experimental investigations were performed by Catano-Lopera and Garcia [6,7] over geometry and migration characteristics of bed forms under waves and currents over sand wave morphdynamics as well as ripples superimposed on sand waves. In their experiments the central area of the wave tank, the bottom was covered by the sand bed of 31 cm thickness, with a median grain diameter 0.25 mm. The flume was filled with water to a level, where the mean water depth was 56 cm above the sand bed. Depth-averaged current velocity was 17 cm/s for coexisting flow tests and the maximum depth-averaged wave velocity ranged from 20 to 60 cm/s. Several conclusions were drawn from the observations: when sand wave heights became comparable to the mean water depth, it was observed that the bottom started to affect the free surface. This in turn modified the surface profile, generating sharpening and sometimes wave breaking, as in the case of a virtual beach. Both sand wave length and height decreased as the wave Reynolds number increased. Dimensionless sand wave migration speed increased as the wave Reynolds number increased. Mazumder and Ojha [31] provided detailed experimental data based on laboratory flume experiments on a smooth surface to investigate the interactions of surface waves with unidirectional current. The findings revealed that the stream-wise mean velocity decreased throughout the depth on the superposition of surface waves of different frequencies. Later Ojha and Mazumder [41] described the turbulent structures over a series of 2-D bed forms in the presence of surface waves. They reported that the effect of surface waves led to increase the flow stability, consequently reducing flow separation and enhanced mixing in the leeside of the waveform. They also observed that Reynolds shear stress increased with superimposed of waves and the maximum increase was attained for 1 Hz frequency of superimposed waves. Mattioli et al. [28,29] performed the experiments on the near bed dynamics around a submarine pipeline on different types of seabed with the interaction between turbulent structures and particles. They clarified the fundamental role played by coherent vortical structures in the interactions of water waves with cylindrical bodies (resembling underwater pipelines) placed on both rigid and erodible beds. They revealed that at wake region of the cylinder, the maximum expansion of dominating vortex indicated the ejection dominated area. Recently, Zhang et al. [63,64] performed the numerical simulation of wave–current interaction related to the solitary wave propagation over a steady current.

In spite of all these studies mentioned above, to the best of the authors' knowledge, no experimental study was performed to simulate the combined wave–current flow over two hemispheres with different spacing, mounted on a flat-surface to examine the perturbed mean flow and turbulence characteristics, despite the fact that such study in the laboratory has the potential to be useful to the researchers, who usually study the effects of submerged obstacles in the natural streams. Therefore, a substantial investigation is required to understand the basic hydrodynamic phenomena experimentally in a flume over these structures in combined wave–current flows. It may be mentioned here that the hemisphere is considered as a 3-D bluff body because important feature of a bluff body flow is that there is a very strong interaction between the viscous and inviscid regions. Separation may occur either from sharp edges or from a continuous surface and create a wake region at downstream of the flow where the negative velocity was found in Bearman [5]. In fact, the hemisphere is a particular case of bluff body.

The main objective of the present study is to investigate the effect of surface waves of different frequencies on the ambient flow over submerged hemispherical obstacles mounted on a rigid flat-surface, which remains unexplored. Further, the aim of this study is to test the effect of deep water and intermediate water wave of different frequencies. More precisely, due to the superposition of the surface waves on the flow over these submerged obstacles, the deviations of mean velocity, turbulence intensities, Reynolds shear stress and the contributions of burst-sweep cycle to the total shear stress are investigated. Experiments are performed using two hemispheres placing them inline arranged along the center line of the flume under combined wave–current flow for the Reynolds number $R_e = 5.88 \times 10^4$. Hitherto it is unclear how the combined wave–current flow is affected by different spacing lengths between the centers of two inline hemispherical submerged obstacles. The velocity data are analyzed to highlight the turbulence statistics and coherent structures in the flow over such spacing between the hemispheres, which were not studied earlier.

2. Experimental setup and procedure

2.1. Test channel

Experiments were conducted in a straight tilting flume (Fig. 1) of 18.3 m length, 0.9 m width and 0.9 m deep of constant hydraulic slope of 0.00025 in the Fluid Mechanics and Hydraulics Laboratory (FMHL), Department of Aerospace Engineering and Applied Mechanics, Indian Institute of Engineering Science and Technology (IIEST), Shibpur, India. 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. The flow at the inlet was passed through a series of