Ocean Engineering 160 (2018) 20–32

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

Combined effect of wave and current in rough bed free surface flow

Santosh Kumar Singh[a,*], Pankaj Kumar Raushan[b], Koustuv Debnath[b]

[a] Department of Mechanical Engineering, SRM Institute of Science and Technology, Kattankulathur, Tamil Nadu, 603203, India
[b] Department of Aerospace Engineering and Applied Mechanics, Indian Institute of Engineering Science and Technology, Shibpur, Howrah, 711103, India

ARTICLE INFO

Keywords:
Cubical roughness
Open-channel
Wave-current
Turbulence
Rough-bed

ABSTRACT

In this paper, detailed experimental results are reported to study the effect of the surface wave of different frequencies on turbulent characteristics of flow over a regular array of cubical roughness. The velocity time series of current-only and combined wave-current flow is analyzed to obtain the distribution of first and the second order turbulence statistics, turbulent kinetic energy production, turbulent dissipation and kinetic energy fluxes at a fixed Reynolds number. To highlight the changes due to combined wave-current flow, a comparative study was made between the velocity profiles for current-only flow and those measured for combined wave-current flow. As expected, the rough profiles are shifted downwards with the amount equivalent to the roughness function (ΔU^+), which was obtained directly from mean velocity profiles. Further, the thickness of turbulent boundary layer increases with the superposition of surface wave compared to current-only flow. Particular attention is also given to understand the behavior of kinetic energy flux to explicitly account for turbulent momentum transport characteristics over roughness under wave-current interactions.

1. Introduction

Flows observed in coastal environments are usually a combination of waves and currents. The presence of surface waves are known to modulate the mean flow and turbulence field which results in an amendment in the momentum transfer, flow resistance and sediment transport characteristics of the flow. Most of both experimental (Brevik and Aas, 1980; Kemp and Simons, 1982; Mazumder and Ojha, 2007; Umeyama, 2005; Singh and Debnath, 2017a; Singh et al., 2018a) and numerical modeling (Grant and Madsen, 1979; Olabarrieta et al., 2010; Teles et al., 2013; Zhang et al., 2014; Tambroni et al., 2015a,b) developed in order to increase the understanding in wave-current interaction, had been taken over a flat surface. In these studies, the emphasis was given to examine the mean velocity profile and how it changes from the universal logarithmic law observed for current-only flow. They also reported the changes in the different turbulence parameters such as turbulence intensity and Reynolds shear stress due to the superimposition of a surface wave on a uniform flow over a flat surface. In addition, the above-mentioned works have contributed to the understanding of the subject, comparatively little is known about the combined wave and current flow over the artificially covered rough bed despite the fact that, such experimentally based information has great importance in practice. The rough bed here investigated is covered with a relatively large array of regular roughness elements, in this case, regular, large-size vortices are routed into the main-stream of the water in a classified manner (both in space and in time). In this respect, Mathisen and Madsen (1996) have conducted experiments in a wave tank with triangular bars as roughness elements. The height and spacing of these elements were chosen such that the bars simulated the ripples. They mainly focused on apparent hydraulic roughness in the case of the combined flow and showed that the apparent hydraulic roughness was underestimated by the model proposed in Grant and Madsen (1979). Fredsoe et al. (1999) performed both experimental as well as the numerical study of the combined wave-current flow over a ripple-covered bed. The ripples used in their work were symmetric. Davies and Villaret (1999) proposed an analytical model to predict the Eulerian drift that is caused by progressive waves over rippled or very rough bed. Ridler and Sleath (2000) studied experimentally the Eulerian time-mean drift induced by progressive waves over the rough bed. Measurements were made in a laboratory flume with a laser Doppler anemometer, and two different two-dimensional artificial bed roughness cases were investigated. The measurements showed that the maximum value of the time-mean drift velocity at the bed might be increased or decreased relative to the value predicted by Longuet-Higgins' theory for smooth beds. Dumas et al. (2005) performed an experimental study in a wave-current co-existing environment to provide a better understanding of the genesis of the

* Corresponding author.
E-mail address: santoshkumarsingh.k@ktr.srmuniv.ac.in (S.K. Singh).

https://doi.org/10.1016/j.oceaneng.2018.04.055
Received 12 September 2017; Received in revised form 13 April 2018; Accepted 16 April 2018

bedforms. They reported that under low orbital velocity, symmetric small ripples became progressively more asymmetric. Ojha and Mazumder (2010) presented the results of an experimental study on the mean flow and turbulence characteristics over a series of two-dimensional (2D) bedforms in the presence of surface waves of different frequencies. Banerjee et al. (2015) performed flume experiments on wind-induced flow in static water bodies in the presence of protruding vegetation. They reported that wave and turbulence effects are simultaneously produced at the air-water interface and the nature of their coexistence is found to vary with different flow parameters including water level, mean wind speed, vegetation density, and flexibility. The more general case of waves superposed to uniform current flowing over a mobile sediment bed covered with vegetation has been addressed experimentally by Tambroni et al. (2015b). Direct numerical simulation of the oscillatory flow close to a wall covered with spherical roughness elements have been performed by Mazzuoli and Vittori (2016) with the aim to identify three flow regimes, which are named the laminar, transitional turbulent and hydrodynamically rough turbulent regimes. They reported that the transition from one regime to the other depends on the Reynolds number and on the diameter of the spheres covering the bed.

In nature, the seabed is covered with 3-D ripples, bars, dunes and great variety of shapes and arrangements of roughness elements having small values of the roughness parameter a/k_s, where a is the amplitude of the orbital motion at the bed and k_s is the Nikuradse's equivalent roughness, which may be taken as 2-2.5k, k being the size of the roughness elements (Dixen et al., 2008). The behavior of wave boundary layer at small values of the roughness parameter a/k_s is important, in connection with the investigation of the stability of rip-rap scour protection in the marine environment where large size of ripples/-stones/rock/armour blocks inevitably leads to small values of a/k_s ($a/k_s = O$ (1), or smaller) as suggested by Dixen et al. (2008). In the present study array of cubes are used as a rough bed with values of roughness parameter similar to that observed in the seabed. Note that, cubes are used in many experimental and numerical studies (e.g., Coceal et al., 2007; Florens et al., 2013) with the advantage of having only one length scale. Thus, a matrix of cubes is ideal for fundamental studies of the flow around roughness elements and above them. Such basic research may be useful in dealing with the morpho-dynamics of alluvial rivers and may be transferable to more natural sea-bed scenarios. Thus, the experimental setting here employed allows for providing some understanding of the turbulence statistics due to combined wave-current flow over the large bottom roughness without adding any difficulty in the measurement procedure. Therefore, the aim of this study is to approach the problem experimentally by measuring the velocity field in a wave-current coexisting environment on a rough boundary created by fixing a large number wooden cube with different relative spacing. The vertical profiles of stream-wise mean velocity and Reynolds stress were obtained from the velocity data collected by an ADV. Additionally, turbulent energy fluxes and energy production for simple current and combined wave-current flows are investigated. The investigators are affirmative that the quantitative analysis reported in the present study will find wide applications in the area of the environmental hydraulics of rough-bed flows and in the understanding of morphodynamic processes like sediment pickup, grain-sorting, and sediment transport over the rough beds with variable spacing between roughness elements.

2. Experimental technique and procedure

The experiments were conducted in the Fluid Mechanics and Hydraulic Laboratory of the Indian Institute of Engineering and Science and Technology (IIEST), Shibpur, India. A specially designed flat-bed open-channel flume of 18.3 m length, 0.90 m width and 0.90 m depth was used for the experiments (Fig. 1). At the downstream section of the flume, waterfalls freely into a large (37 m long, 8 m wide and 2 m deep) sump from where it is recirculated into the flume using a vertical turbine pump (located outside the main body of the flume). Waves were generated along the unidirectional current by a plunger type wave-maker placed at the upstream end of the flume. The wave-maker was connected to a variac in order to control the frequency of oscillation. The basic details of wave-maker and its working principle are reported in Singh and Debnath (2016, 2017b). The pump system circulated the water from the large sump, and flow depth ($h = 20$ cm) was kept constant throughout the experiments by adjusting the discharge valve and tail-gate simultaneously.

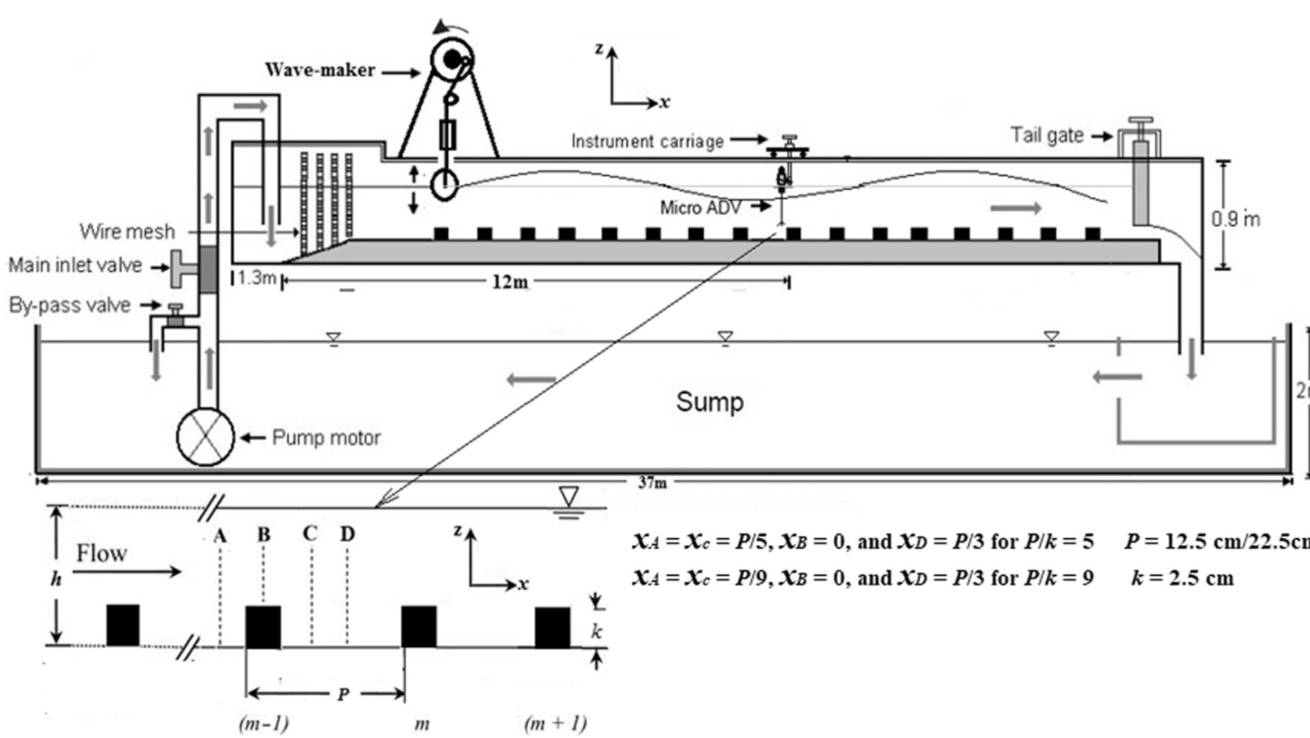

Fig. 1. Schematic of the experimental set-up with cube mounted rough-bed along with the measuring locations A, B, C and D. The flow direction is from left to right.