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Experimental investigation of the impact of macroalgal mats on the wave and current dynamics

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ABSTRACT

Macroalgal mats of *Ulva intestinalis* are becoming increasingly common in many coastal and estuarine intertidal habitats, thus it is important to determine whether they increase flow resistance, promote bed stability and therefore reduce the risk of erosion favoring tidal flooding or degradation of coastal lagoons. Venier et al. (2012) [6] studied the impact of macroalgal mats of *Ulva intestinalis* on flow dynamics and sediment stability for uniform flow. Here we extend their experimental work to the case of vegetation under the combined action of waves and currents. These hydrodynamic conditions are very common in many shallow coastal environments and lagoons. The experimental facility employed in the present study and the series of flow runs are the same as that used by Venier et al. (2012)[6]. However, waves have been superposed to uniform current flowing firstly over a mobile sediment bed covered with *U. intestinalis*, then over a bare sediment surface. For the depth, wave and current conditions considered in the experiments, the time-averaged vertical profile of horizontal velocity for the case of coexisting waves and current turns out to be very close to that observed for a pure current, both with and without vegetation. However, contrary to what was observed in the case of a unidirectional current, in the presence of waves the time averaged velocity profile is only weakly influenced by the vegetation, whose main effect is to attenuate velocity oscillations induced by waves and to slightly increase the overall bed roughness.

1. Introduction

Due to the observed increase of macroalgal mats in many coastal and estuarine intertidal habitats [1,2], the scientific community has been recently tasked with improving the present state of knowledge on role of macroalgae in shallow coastal ecosystems. From a hydrodynamical and morphodynamical point of view the issue has recently been addressed by Venier et al. [6]. This experimental study provided an overview of how *Ulva intestinalis* affects unidirectional flow over a sandy bed. The data collected for a range of flow depths that is typical of tidal environments suggest that macroalgae exert a significant stabilizing effect even when the algal cover is sparse. As documented by direct observations and bed elevation measurements, and unlike most of the plants used in other laboratory flume studies [36,37], this species of macroalgae tend to lie flat over the bed, moving sinusoidally with the current. The interaction of the macroalgae with the flow results in a decreased bedform amplitude, with small bedforms forming around the macroalgae strands. In other words, *Ulva intestinalis* provides shelter to sediment grains on the bed, changing the morphology and migration rate of bedforms. Moreover, the interaction of the fronds and bedforms results in an upward shift of the roughness sublayer, where shear stress is more intense. The resulting vertical distributions of the longitudinal velocity and of shear stress suggest that macroalgae lead to a decrease of the near bed mean velocity and an increase of the overall flow resistance. The total friction velocity is generally greater over macroalgae than over bare bed. The presence of macroalgae, however, also contributes to a reduction in the effective bed shear stress associated with skin friction, responsible for sediment motion. The overall sediment mobility, and hence the amount of transported sediment, are thus reduced. Note that the study of Venier et al. [6] focused on macroalgal mat interactions with steady unidirectional flow conditions. Nevertheless, both temporal and spatial flow dynamics are crucial to fully understand the momentum transfer mechanisms and their influence on flow resistance [24,25]. Here, we complement the above analyses by assessing the influence of macroalgal mats on sediment transport in wave-current

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induced flows. Most of previous studies, conducted in the field or in the laboratory to understand the interaction between hydrodynamics and vegetation, considered the case of flow driven by either an uniform current or by regular waves (e.g., [3,4,18–21]). Few observations have been performed including both the effects of currents and waves over a vegetated bottom [22,23].

On the other hand, many efforts have been carried out by the scientific community with the purpose of analyzing wave-current non-linear interactions in the simplest case of an unvegetated bottom. Laboratory experiments ([7–11,26–28] among others) showed that when waves and currents coexist, the steady profile of longitudinal velocity changes the logarithmic shape observed for pure current conditions. In particular, Kemp and Simons [8] showed that mean longitudinal velocities close to a smooth bed increase in the presence of waves, whereas they reduce near a rough bed. Furthermore, when waves propagate in an opposite direction with respect to the current, the longitudinal current intensity reduces near to the bed. Musumeci et al. [27] showed that if the bed is smooth, an increase of the near bottom velocities occurs when waves are perpendicular to the current. The opposite happens when the bottom is rough. Moreover, observed current profiles suggest that wave-current interaction effects are not restricted to the near bottom region, but influence the entire water column [7–10]. These effects mainly depend on the propagation directions of waves and currents. While for parallel and perpendicular cases a reduction of the current intensity is observed in the region below the wave trough, the contrary occurs for opposing waves and currents. As suggested by Kemp and Simons [9], variations of steady current profile also depend on wave amplitude and on water depth. In addition to experimental studies, various analytical and numerical models have been developed to describe the bottom boundary layer flow under waves and currents. Here we mention the models of Grant and Madsen [5], Fredsoe [29] and Davies et al. [30]. We refer the interested reader to Olabarrieta et al. [31] and Tambroni et al. [32] for an overview of more recent contributions to the mathematical study of wave-current interactions.

The combination of wave characteristics and current speed investigated here, are those typically found in intertidal areas, supporting macroalgae growth within coastal lagoons dominated by tidal action. In particular, we focus on flow fields that are characterized by relatively low values of the ratio between the amplitude of horizontal orbital velocity and the current velocity (i.e., strong current - weak wave). The main aim of this paper is to compare the behaviors of a bare sediment bottom and of a sediment bottom covered by macroalgae under the combined action of waves and currents through the analysis of the vertical distribution of stationary velocity profiles and turbulent Reynolds stresses.

The body of the paper is organised as follows. In Section 2 we briefly describe the experimental apparatus and the test configuration. Section 3 is devoted to the analysis of velocity data collected in the tests, with particular reference to the characteristics of turbulence observed with and without waves. Finally, Section 4 reports some conclusions and suggestions for future research.

2. Materials and methods

2.1. Experimental facility

Experiments were carried out in the Total Environment Simulator (TES) recirculating flume at the University of Hull (UK), equipped both with pumps to generate flow and paddles to generate waves. The experimental facility is the same described in detail by Venier et al. [6], therefore we will just briefly summarize the main characteristics of the experimental setup. Length and width of the flume tank were 11 m and 2 m, respectively. Experiments were conducted over a mobile bed, with and without vegetation, in the presence of both waves and currents. In particular, sediment chosen for the experiments was a non-cohesive, unimodal and well-sorted fine sand, characterized by a median grain size of 0.135 mm, which is similar to that of the sediments covering the tidal flats of Budle Bay (NE, England), where strands of *Ulva intestinalis* were collected for the present tests. This is a common macroalga which can be very abundant in nutrient enriched coastal systems. The algae was planted, following the regular pattern shown in Fig. 1, in a 20 cm thick sediment bed that was leveled before the start of the experiments. The density of the plantings (12 plants per m^2) intended to represent a sparse algal mat cover (~30%) and was characterized by a lateral and longitudinal spacing equal to 20 cm and 40 cm, respectively. The large number of fronds attached to each strand generated a fan shape covering up to 20 by 10 cm of the sandy bed.

Table 1
Summary of the experimental tests, carried out for three different water depths under either unidirectional current (subscript *c*) [6] or waves superposed to a uniform flow (subscript *wc*), and a sandy bed either bare (*B* tests) or covered with macro algae (*M* tests). Notations are as follows: D: depth of the still water initially filling the flume; Q: water discharge used to obtain a uniform unidirectional flow; H_w: wave height; T_w: wave amplitude; L_{th}: wave length according to the dispersion relation provided by the linear Stokes theory; U_x: depth averaged value of the spatially and time averaged longitudinal velocity; L_{bf}: observed bedform wavelength; Q_s: measured mass sediment flow rate per unit width transported as bedload.

Run	$M1_c$ $B1_c$	$M1_{wc}$ $B1_{wc}$	$M2_c$ $B2_c$	$M2_{wc}$ $B2_{wc}$	$M3_c$ $B3_c$	$M3_{wc}$ $B3_{wc}$	Bed
D (m)	0.22	0.22	0.25	0.25	0.31	0.31	
Q (l s^{-1})	90	90	102	102	124	124	
H_w (m)	–	0.09	–	0.10	–	0.12	
T_w (s)	–	1.0	–	1.0	–	1.1	
L_{th} (m)	–	1.25	–	1.30	–	1.60	
U_x	0.22	0.24	0.26	0.254	0.26	0.23	M
(m s^{-1})	0.23	0.26	0.28	0.23	0.27	0.27	B
L_{bf}	10.4	6.6	11.7	6.8	10.2	6.8	M
(cm)	9.8	7.3	–	8.2	12.4	8.5	B
Q_s	–	8.11	0.60	13.00	0.06	9.80	M
(10^{-4} kg m^{-1}s^{-1})	0.67	9.90	–	12.00	0.50	12.0	B

Velocity measurements were collected in a 2 m wide and 2 m long sampling volume placed approximately at the centre of the flume (see Fig. 1 of Venier et al. [6]). This measuring area was located 6 m downstream of the flume inlet, to ensure fully developed, uniform flow conditions and to enable wave form development. The longitudinal, lateral and vertical velocity components, (u_x, u_y, u_z), were measured at a set of selected points by means of four Nortek laboratory ADVs, denoted as ADV0, ADV1, ADV2, ADV3 in Fig. 2. These devices were located 1.2, 1.1, 1.0 and 0.9 m from the flume wall and were moved longitudinally to monitor the along-flow positions X_1, X_2, X_3, X_4 located 0.8, 1.0, 1.2 and 1.4 m from the upstream limit of the measuring area. Up to 10 different points, depending on the flow depth, were sampled at each given vertical and velocities were sampled at a frequency of 25 Hz for an acquisition time of 120 s. The ADV sampling volume was approximately 350 mm^3.

The total mass of sediment transported along the flume as bedload was measured at the end of each run by weighing sediment collected within a series of pit-type traps located across the downstream end of the flume.

2.2. Experimental programme

As reported in Table 1, the experimental programme involved three runs (hereafter denoted by the subscript 'wc' to indicate the combined wave–current conditions) conducted for three different water depths in the presence of both a unidirectional flow and a monochromatic, regular train of waves. The water depths and pumping discharges imposed in the experiments were selected in order to ensure the same mean flow conditions employed in the experiments of Venier et al. [6], typical of micro-tidal environments. The