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Wave and vegetation effects on flow and suspended sediment characteristics: A flume study

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Abbreviations:
ADV
acoustic Doppler velocimeter
COR
correlation
DTFT
discrete-time Fourier transform
FFT
fast Fourier transform
SNR
signal-to-noise ratio
SSC
suspended sediment concentration
TKE
turbulence kinetic energy

ABSTRACT

Vegetation in tidal flats can alter flow dynamics by increasing the velocity gradient and attenuating the wave energy. In this study, a flume experiment was performed using the pioneer plant *Scirpus mariqueter* and suspended sediment. Two cases are analysed: current-only and current-wave conditions with a regular wave. A statistical method is used to analyse the average velocity and the turbulence intensity. Results demonstrate that the plants can cause a velocity decrease in the vegetation region and an increase in the turbulence intensity below the top of the canopy. The combined effect of waves and vegetation on turbulence dramatically increases the flow velocity above the average water depth as well as the turbulence intensity profiles. In this study, the attenuation efficiency of the wave height is 0.0448 m^{-1}, which is identical to results using artificial plants with the same relative submerged depth. The drag force in current-wave conditions is almost twice of that observed in current-only conditions. The spectral analysis shows that only waves can influence high-frequency motion. In addition, an increase is observed in the bottom shear stress, mean grain size, and suspended concentration of the sediment during current-wave conditions.

1. Introduction

Vegetation in tidal flats is important for protecting the land from erosion and for improving habitat development. It is therefore relevant to study the effect of vegetation on the flow structure and movement of fine suspended sediment during current-wave processes. However, interactions between waves and vegetation inside the canopy are complicated. Over the last three decades, numerous studies have been devoted to this issue, including experimental, theoretical, and numerical contributions (Knutson et al., 1982; Kobayashi et al., 1993; Mendez and Losada, 2004; Möller, 2006; Hu et al., 2014).

Due to the blocking effect and specific characteristics of plants, such as height and flexibility, vegetation can greatly influence the flow velocity, turbulence intensity, Reynolds stress, and bottom shear stress. In addition, various configurations and density contribute to different flow structures within submerged flexible vegetation region (Chen et al., 2011). In open-channel flow, this issue has been well studied, both from field investigations (Leonard and Reed, 2002; Lacy and Wyllie-Echeverria, 2011) and indoor flume experiments (Järvelä, 2002; Montakhab and Yusuf, 2011). “Skimming flow””, defined as a relatively fast flow above a lower

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layer that is characterized by significantly slower velocities, has also been investigated (Neumeier and Ciavola, 2004; Wilkie et al., 2012). In tidal flats, flow can be influenced by both waves and vegetation, e.g., stem-wake-turbulence (Pujol and Nepf, 2012), and waves can also be attenuated by vegetation. Because both waves and vegetation can influence the velocity and the turbulence, it is necessary to discriminate between different wave contributions.

The wave height attenuation rate (defined as the relative decrease in wave height/energy per unit distance) varies with water depth (Augustin et al., 2009), shoot density (Paul and Amos, 2011; Stratigaki et al., 2011), and land slope (Henry and Myrhaug, 2013). To estimate the attenuation effect, the wave height attenuation rate is defined (Koftis et al., 2013) as:

$$A_v = \frac{H_x}{H_0} = \frac{1}{1 + \beta_c x} = e^{-k \cdot x} \tag{1}$$

where A_v is the relative wave height attenuation, H_x is the wave height at distance x in a canopy, H_0 is the wave height at the upstream edge of the canopy, $\beta_c\,(\mathrm{m}^{-1})$ is the coefficient, and $k\,(\mathrm{m}^{-1})$ is the decay coefficient. Because wave attenuation is a function of the plant characteristics and near-shore hydrodynamics, the k parameter is normally used to represent the attenuation ability. Based on previous studies, Table 1 summarises the coefficients of k for several species, including natural and artificial plants.

The hydrodynamics inside the canopy can vary with respect to the species involved. The most accepted hypothesis is that energy loss over the vegetated field is due to drag forces (Koftis et al., 2013). Chapman et al. (2014) directly measured hydrodynamic forces on individual plant shoots using a torque sensor, and the collected data suggested that more flexible objects result in a lower drag force coefficient (C_D). As it is difficult to measure the drag force directly (Tempest et al., 2015), many studies have adopted an empirical formula. The most frequently used empirical relationship, developed by Kobayashi et al. (1993), has the following basic form:

$$C_D = \alpha + \left(\frac{\beta}{\mathrm{Re}_*}\right)^{\gamma} \tag{2}$$

In this equation, α, β, and γ are coefficients, $Re_* = U_t\, b_v/\upsilon$ is the Reynolds number based on the plant stem diameter b_v, the velocity U_t is a characteristic velocity acting on the plant and is defined as the maximum horizontal velocity at the top of the vegetation, and υ is the kinematic viscosity of water. Jadhav et al. (2013) proposed a rigid-type vegetation model to estimate the frequency-dependent bulk drag coefficient. It also has been proven that the three coefficients α, β, and γ are related to the plant type. Table 2 lists the typical values of these three coefficients. Although there are many results using a variety of species, obtaining the general rule for wave height attenuation requires further and broader study.

In addition to the Reynolds number, the C_D can also be expressed in terms of other parameters: the Keulegan-Carpenter number ($K_C = U_t T/b_v$, where T is the wave period) or the modified Keulegan-Carpenter parameter $Q = K_C/(h_v/h)^{1.5}$, where h_v is the average stem length and h is water depth (Anderson and Smith, 2014). An equation frequently used in literature (Mendez and Losada, 2004; Augustin et al., 2009) is:

$$C_D = \frac{\exp(-0.0138Q)}{Q^{0.3}}\,(7 < Q < 172) \tag{3}$$

In theory, interactions between the waves and the vegetation occur over a wide range of time scales. Therefore, wave energy loss exists at all frequencies of the spectrum. Wave energy might not be dissipated at the same rate amongst the different wave frequency components (Madsen et al., 1988). A more fundamental discussion on the variation of the full frequency spectrum under wave breaking and interaction with the vegetation element can be found in Massel et al. (1999). Furthermore, Anderson and Smith (2014) studied the transformation of single- and double-peaked wave spectra due to vegetation with a focus on frequency-dependent attenuation.

In addition to vegetation, suspended sediment can also dissipate the wave energy; therefore, study of wave dissipation in turbid water is required. In a tidal flat with vegetation, high wave energy can penetrate through the canopy to the bed and the sediment close to the bottom can be stirred by waves and entrained by the current. Specifically, bottom shear stress and sediment entrainment are affected by current-waves, thereby contributing to erosion or deposition in coastal zones (Hansen and Reidenbach, 2012). It was reported that the vegetation *Posidonia oceanica* significantly buffered sediment re-suspension, which was reduced more than threefold compared to a non-vegetated bottom (Gacia and Duate, 2001). Davidson-Arnott et al. (2012), through field investigations, stated that local variations in vegetation density and height (i.e., patchiness) likely accounted for some of the high-frequency variations in sand transport intensity, as well as spatial differences. This process can be represented using the grain size distribution of several layers along the water depth. Generally, the mean grain size in low marsh zones is larger than that in high marsh zones (Wu et al., 2011, 2013), and the intertidal environment can also affect sediment distribution (Cooper, 2005).

Table 1
A comparison of wave attenuation coefficients.

Studies	Marsh species	Distance (m)	A_v (%)	$k\,(\mathrm{m}^{-1})$
Field measurements				
Knutson et al. (1982)	*Spartina alterniflora*	30	94	0.0938
Möller et al. (1999)	Diverse saltmarsh	180	54	0.0043
Cooper (2005)	Diverse saltmarsh	330	91	0.0073
Mazda et al. (2006)	*Sonneratia* sp.	100	60	0.0092
Möller (2006)	*Spartina* and *Salicornia*	10	30	0.0357
Bradley and Houser (2009)	Diverse saltmarsh	39	30	0.0091
Ysebaert et al. (2011)	*Scirpus mariqueter*	50	80	0.0322
Paul and Amos (2011)	*Zostera noltii*	58	20	0.0038
Jadhav et al. (2013)	*Spartina alterniflora*	28	62	0.0349
Laboratory experiments				
Tschirky et al. (2000)	*Scirpus validus*	10	40	0.0511
Augustin et al. (2009)	*S. alterniflora*	6	24	0.0457
Stratigaki et al. (2011)	Artificial *Posidonia oceanica*	10	28	0.0322
Wu et al. (2011)	*Spartina alterniflora*	8	38	0.0613
Manca et al. (2012)	Artificial *Posidonia oceanica*	10	25	0.0288