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Experimental observations on sediment resuspension within submerged model canopies under oscillatory flow

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ABSTRACT

A set of laboratory experiments were conducted to study the effect of submerged aquatic vegetation in sediment resuspension under progressive waves. Three vegetation models (rigid, flexible and real plants of *Ruppia maritima*), six wave frequencies (in the range $F=0.6$–1.6 Hz) and four plant densities (Solid Plant Fractions, *SPF* in the range of 1–10%) were used. The sediment bed properties corresponded to a salt marsh wetland with a bimodal particle size distribution with two particle populations (population 1: particle diameters in the range of 2.5 to 6.0 μm, and population 2: particle diameters in the range of 6.0 to 100 μm).

Within the canopy, wave velocities were attenuated for all the canopies studied and for all the frequencies analyzed. The change in the *TKE* (ΔTKE) compared with the case without plants was studied. For the rigid canopy model, in comparison to the unimpeded experiment, an increase in ΔTKE inside the canopy for smaller frequencies ($F=0.6$–1.2 Hz) was observed together with stem Reynolds numbers Re_p above 250. As a result, sediment resuspension for both sediment populations was higher than that of the unimpeded experiment. However, at higher frequencies ($F=1.4$ and 1.6 Hz) and higher plant densities ($SPF=5\%$, 7.5% and 10%), the ΔTKE inside the canopy decreased, coinciding with stem Reynolds number Re_p below 250. As a result, sediment resuspension for larger canopy densities and larger frequencies was reduced.

For the flexible vegetation model, in comparison with the unimpeded experiment, a reduction in the ΔTKE inside the canopy was nearly always found. Resuspended sediment concentrations were found to decrease as flexible canopy densities increased. For the flexible vegetation the stem Reynolds number was $Re_p < 250$ and no production of ΔTKE was observed. The real case of a canopy of *R. maritima* behaved similarly to the flexible model canopy.

1. Introduction

Seagrasses and salt marshes are ecosystem engineers with the well-known function of reducing the action of waves and storm surges (Granata et al., 2001; Türker et al., 2006). Sheltering is characteristic of dense canopies, where turbulence cannot penetrate deep into the canopy, and flushing is controlled by the stem-scale turbulence (Nepf et al., 2007). Under wave-dominated flows, near-bed turbulence levels within seagrass canopies are lower than those on bare soils (Granata et al., 2001; Hendriks et al., 2008; Pujol et al., 2013). As a consequence, wave energy and sediment resuspension are reduced by seagrasses (Terrados and Duarte, 2000; Bouma et al., 2005; Infantes et al., 2012; Paul et al., 2012). In addition, the reduction in sediment resuspension improves water clarity, which in turn, provides greater light penetration and consequently an increase in productivity, thus creating a positive feedback for the sea and wetland grasses growth (Ward et al., 1984; Koch, 2001).

The reduction of sediment resuspension within the canopy is directly linked to the modification of currents, wave velocity and turbulence (Neumeier, 2007; Pujol et al., 2013) as well as to the intrinsic properties of the canopy itself, canopy density and flexibility of plants. As pointed out by van Katwijk et al. (2010) at the relatively wave-exposed, sandy sites, dense vegetation cause muddification (increase in fine sediments and organic content) of the sediments. In contrast, in sheltered sites with muddy sediments, dense vegetation has no effect on the sediment composition. In sparse sheltered vegetation, contrary to non-sheltered canopies, with muddy sediments, sandification (decrease in fine sediments and organic content) prevails. In events where the flow level is above the vegetation, sedimentation decreases with distance, from the seaward marsh edge and from the creeks, in parallel with a grain-size fining or muddification (Neumeier and Amos, 2006). Coastal zones present a large variety of clay, silt and

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sand composition. Different particle sizes compose the sediment bed in view of their density and settling velocity and are prone to differential resuspension when facing an external physical forcing. Therefore, sediment resuspension will highly depend on the characteristics of plants as well as on the intensity of reduction of wave velocity by the canopies and the generation of turbulent kinetic energy through the interaction between waves and the canopy.

The attenuation of the flows inside canopies has been studied by Lowe et al. (2005a, 2005b). The authors conducted laboratory experiments and developed an analytical model to investigate the flow structure inside a submerged canopy, such as a coral reef. Their model was developed by considering the momentum balance around individual canopy elements within a larger canopy. They demonstrated that the flow inside a canopy was always lower than above the canopy, and that the degree of flow attenuation varied as a function of canopy geometry parameters, such as the height and spacing of the elements, as well as coefficients that parameterize the effects of various forces exerted by the canopy element. The canopy flow attenuation was found to depend on the non-dimensional parameter A_w/S where A_w is the wave orbital excursion length and S is defined as the edge-to-edge average distance between closest elements in any direction. This ratio has been called the Keulegan–Carpenter number (Monismith, 2007), although for Mendez and Losada (2004) the definition of this number is slightly different (S was defined as the plant area per unit height of each vegetation stand normal to the wave velocity). The two definitions of S are proportional and give account of the density of the canopy. When A_w/S is large, the flow is drag dominated and velocities inside the canopy are much lower than in the free stream. In contrast, when A_w/S is small, the interstitial flow is inertia dominated and interior velocities more nearly match exterior ones, and total mass transfer is enhanced over that of steady flows. This paper aims at understanding the relationship between the turbulent kinetic energy, the shear stress and sediment resuspension in terms of the canopy density and depending on whether the stem is flexible or rigid. The environmental flow under study is a field of monochromatic waves. The wave frequency is also a key parameter that will be analyzed in the present work.

2. Materials and methods

2.1. Experimental setup

The study was conducted in a 6 m × 0.5 m × 0.5 m wave flume. A scheme of the setup is shown in Fig. 1. The mean water depth, h, was 0.3 m. A plywood beach, with a slope of 1:3 and covered with a 7 cm layer of foam rubber, was located at the end of the flume. A vertical paddle, called a flap type wavemaker, was placed at the front of the flume and was driven by a variable-speed motor with a constant stroke of 5 cm and a variable frequency F in the range from 0.6 to 1.6 Hz (Table 1). Since $\lambda/2$ was always larger (Table 1) than the water depth (of 30 cm), the generated waves always reached the bottom of the flume (where λ is the wave length). Furthermore, since $\lambda/20 < h < \lambda/2$, these waves corresponded to waves in transitional waters, i.e. intermediate to shallow waves, which are in accordance with the typical waves in vegetated coastal regions. We defined the longitudinal direction as x, and $x=0$ was the longitudinal position at the wavemaker. $y=0$ at the centerline of the tank and z is the vertical direction, $z=0$ corresponded to the depth at the flume bed. Wave conditions in the present study corresponded to the laminar regime, i.e. to wave Reynolds number, $Re_w = U_{w,\infty} A_\infty / \nu < 10000$, where $U_{w,\infty}$ represents the orbital wave velocity unaffected by the canopy roughness (i.e. the wave velocity far above the canopy, here considered at $z=22$ cm above the bottom), called free-stream velocity, and A_∞ is the wave orbital excursion length of the free-stream potential flow. The submergence ratio, defined as h_v/h (where h_v is the plant height), was 0.47, which falls in the upper limit of those used in other studies (Manca et al., 2012).

2.2. Vegetation models

The rigid canopy model consisted of rigid PVC cylinders 1 cm in diameter and 14 cm long. Different canopy densities were also considered in the experiments. According to Pujol et al. (2010), the canopy density can be defined as the solid plant fraction at the bottom occupied by stems, $SPF = 100 \cdot n\pi(d/2)^2/A$, where n is the number of plants, d is the diameter of the model plant, and A is the planform area. *SPF*s of 1%, 5%, 7.5% and 10% were used for experiments with submerged rigid vegetation, *SPF*s of 1%, 5% and 10% were used for those experiments with submerged flexible vegetation and 1% for those with real plants (Table 1). The vegetation pattern for each *SPF* was made at random by means of a computer function (Pujol et al., 2013). A plastic board was regularly perforated with holes of 1 cm with a distance of 1.5 cm between the centers of two neighbor holes. The random pattern of vegetation was made filling the corresponding holes with the cylinders and leaving some holes at the bottom that where afterwards filled with small dowels with the length equal to the bottom board thickness. The same procedure was repeated for each *SPF*.

The flexible canopy model was constructed with implants of polyethylene (high density) blades attached with a plastic band to a PVC dowel 2 cm long and 1 cm in diameter. Each plant had eight plastic blades of 4 mm width. The model plants were dynamically and geometrically similar to typical seagrasses, as described by Ghisalberti and Nepf (2002), Folkard (2005) and Pujol et al. (2013). The canopy density for flexible plants was calculated based on the area occupied by the dowels that fixed the plants at the bed.

The real plant model consisted of *Ruppia maritima*, which is a typical plant found in salt marshes and especially abundant in the Mediterranean coastal areas. It produces long, narrow, straight leaves and is characterized by seasonally contrasting growth of tall flowering reproductive shoots in mid-summer and shorter vegetative roots during the remainder of the growing season. The plants for the model were cut to a height of $h_v = 14$ cm, so that results could be compared with those obtained for the rigid and flexible canopy models. The real plant blades were attached to the same PVC dowels used for the flexible canopy model.

2.3. Measuring technique

The Eulerian velocity field was defined as (u, v, w) in the (x, y, z) directions, respectively. The three components of the velocity were recorded with a downwards looking Acoustic Doppler Velocimeter (Sontek/YSI16-MHzMicroADV). The acoustic frequency was 16 MHz, the sampling volume was 0.09 cm^3 and the distance to the sampling volume was 5 cm. The ADV sampled at 50 Hz, limiting the velocity spectra to 25 Hz due to Nyquist frequency. The ADV was mounted on a movable vertical frame that allowed it to be manually situated at working depths of $z=5$ cm (i.e. $z/h_v = 0.4$), well inside the canopy model, $z=15$ cm (i.e. $z/h_v = 1.1$) and $z=22$ cm (i.e. $z/h_v = 1.6$), these two last depths corresponding to the layer above the canopy models. It measured during 20 min at each depth. After measuring at one depth it was moved vertically and left for 15 min before measuring again. Each experiment lasted 120 min. To avoid spikes due to poor correlations, ADV measurements with beam correlations below 80% along and