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Wave energy and wave-induced flow reduction by full-scale model *Posidonia oceanica* seagrass

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ABSTRACT

This paper presents results from experiments in a large flume on wave and flow attenuation by a full-scale artificial *Posidonia oceanica* seagrass meadow in shallow water. Wave height and in-canopy wave-induced flows were reduced by the meadow under all tested regular and irregular wave conditions, and were affected by seagrass density, submergence and distance from the leading edge. The energy of irregular waves was reduced at all components of the spectra, but reduction was greater at the peak spectral frequency. Energy dissipation factors were largest for waves with small orbital amplitudes and at low wave Reynolds numbers. An empirical model, commonly applied to predict friction factors by rough beds, proved applicable to the *P. oceanica* bed. However at the lowest Reynolds numbers, under irregular waves, the data deviated significantly from the model. In addition, the wave-induced flow dissipation in the lower canopy increased with increasing wave orbital amplitude and increasing density of the mimics. The analysis of the wave-induced flow spectra. Finally, we discuss the implications of these findings for sediment dynamics and the role of *P. oceanica* beds in protecting the shore from erosion.

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1. Introduction

Coastal benthic habitats, such as coral reefs, saltmarshes and seagrass beds, are widely recognized in helping to protect the shoreline from erosion and for acting as "buffers" against storm surge effects by reducing wave energy and stabilising the seabed. The benefits derived from ecosystem services, such as wave attenuation and coastal protection, have a specific value which is often variable in space and time (Koch et al., 2009). In the Mediterranean, the large perennial *Posidonia oceanica* seagrass, forms vast meadows and colonizes seabeds from the surface to about 40 m depth (Gobert et al., 2006). *P. oceanica* is included in the Barcelona Convention's list of protected species (Cavazza et al., 2000), and is listed in the Habitats Directive (43/92 CEE) as a Priority habitat for conservation, as it supports an important coastal ecosystem, by providing food, refuge and nursery areas for

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species of large economical and ecological importance. Like other seagrass species, it affects hydrodynamic conditions which in turn control sediment re-suspension (Gacia and Duarte, 2001; Gacia et al., 1999) as well as key ecological processes such as nutrient uptake, larval dispersal and recruitment (Koch et al., 2006a). Hydrodynamic conditions also affect the distribution of seagrass and, in general, in wave-dominated environments, seagrasses are found where waves are of the intermediate type (ratio of depth, *D*, to wave length, λ , between $1/20 < D/\lambda < 1/2$) (Koch et al., 2006b). The upper depth limit of a *P. oceanica* meadow can also be determined by near-bottom wave orbital velocities, between 38 cm/s and 42 cm/s (Infantes et al., 2009).

Wave energy dissipation (wave energy loss with distance from the leading edge of the meadow) due to vegetation has been documented in several studies (for example Fonseca and Cahalan, 1992; Koch et al., 2006b), however the physical mechanisms controlling wave transformation over submerged canopies are not fully understood and the effect of individual parameters on wave/ vegetation interactions are still not clear. The effect of plant density, for example, is still controversial: some studies found density enhances wave height reduction (Bouma et al., 2005; Penning et al., 2009), others found it has no effect (Augustin et al., 2009; Fonseca and Cahalan, 1992). The situation is further complicated because another study showed that a minimum

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density threshold is required to initiate wave attenuation (Paul and Amos, 2011). Detailed studies of wave-vegetation interactions, under controlled conditions, have been performed mainly with scaled models (Asano et al., 1988; Dubi and Tørum, 1994; Elginoz et al., 2011; Løvås and Tørum, 2001; Sanchez-Gonzalez et al., 2011), with results difficult to extrapolate to full scale real conditions. The relationship between wave height reduction and wave period in seagrass canopies is not known and the interaction between storm waves and seagrass needs defining (Koch et al., 2006b). Wave height decay across vegetation has often been used to evaluate its capacity to attenuate waves. Several field studies have shown that most of the wave height reduction occurred in the first few metres of a vegetation field: wave energy dissipation was found to be maximum at the front of salt-marshes (Möller et al., 1999), beds of Laminaria hyperborea kelp (Dubi and Tørum, 1994) and shallow seagrass (Bradley and Houser, 2009). Wave height decay over submerged vegetation has generally been expressed by an exponential function of the type:

$$\frac{H(x)}{H_0} = e^{-K_i \Delta x} \tag{1}$$

(Kobayashi et al., 1993) where K_i is the wave decay coefficient, H(x) is the wave height measured along the vegetation field, Ho is the wave height in front of the leading edge of the field, and Δx , the separating distance.

Wave energy dissipation over a roughness (f_e), or wave friction factors at the bed (f_w) have often been expressed as a function of the wave orbital amplitude (A) and a roughness parameter (r). The hydraulic roughness (r, as defined in Nielsen, 1992) is associated with the vertical length scale of the wave boundary layer and the physical size of the roughness elements. In general, f_e is smaller than the friction factor at the bed, however Nielsen (1992) derived f_w from f_e measurements and found that they can be assumed to be equal. For fully-rough turbulent flows, several formulations have been proposed to calculate f_w , (such as those of Swart (1974), Soulsby (1997) or Nielsen (1992)) The equation by Nielsen (1992) is a modification of Swart's formulation and it is given below:

$$f_{\rm w} = \exp\left[5.5\left(\frac{r}{A}\right)^{0.2} - 6.3\right] \tag{2}$$

Derived empirically from a large series of laboratory experiments on friction over surfaces of known physical roughness. It has been used widely and it has been successfully applied to obtain f_w over very rough surfaces, such as coral reefs (Lowe et al., 2005a) and to estimate the hydraulic roughness of the bed. However, the application of the r parameter to flexible vegetation is unproven (Paul and Amos, 2011).

Furthermore, wave energy might not be dissipated at the same rate amongst the different frequency components of the waves (Madsen et al., 1988). There is evidence that rigid canopies (Lowe et al., 2007, 2005b) and submerged vegetation (Bradley and Houser, 2009) are more efficient at attenuating short period components of the wave energy spectrum. Wave energy dissipation by submerged vegetation depends upon several factors such as vegetation characteristics, weather and general hydrodynamic conditions, as well as bathymetry and sediment characteristics prevalent in the region of study (Koch et al., 2009; Möller et al., 2002). It is unlikely that a common behaviour prevails for all types of vegetation and conditions (Mendez and Losada, 2004). However, the definition of a parameter, such as a friction factor for different types of vegetation is highly desirable and could be used for modelling vegetation effects on coastal environments. According to several studies (Bradley and Houser, 2009; Kobayashi et al., 1993; Mendez et al., 1999) the drag induced by submerged vegetation depends upon the vegetation Reynolds number, $(Re_v = bU_b/v)$, therefore, for a given width of the blades/leaves (b) and water kinematic viscosity (v), the drag is directly dependent on the wave-induced characteristic velocity acting on the vegetation (U_b). In rigid canopies a key element in the wave energy dissipation processes is the dissipation of wave-induced flows (Lowe et al., 2007). From the analysis of the changes of the oscillatory flow attenuation parameter (α_w the ratio of the in-canopy velocity to the free stream velocity) with A, in canopies made of rigid cylinders, regular short-period waves are capable of driving more flow through the canopy than large amplitude waves, or unidirectional flows (Lowe et al., 2005b).

Studies on the interactions between aquatic vegetation and oscillatory flows are scarce and this has been identified as an important area for research, especially with respect to seagrass species (Bouma et al., 2007; Fonseca et al., 2006; Koch et al., 2006b). Most knowledge of the flow dynamics in and around canopies comes from measurements performed under unidirectional flows (Leonard and Luther, 1995; Neumeier and Ciavola, 2004; Thompson et al., 2004). More specifically, prior to the study presented here, detailed studies on flow variations due to P. oceanica have only been carried out in small flumes and under unidirectional flows (Ciraolo et al., 2006; Folkard, 2005; Maltese et al., 2007). An in-situ study of P. oceanica, was carried out on a 15 m deep meadow off the Catalan coast and found that a meadow reduces currents (Gacia et al., 1999) and wave orbital velocities within the canopy (Granata et al., 2001). In a flume study with artificial canopy of Zostera marina seagrass, Luhar et al. (2010) found that oscillatory flows were not significantly reduced (reduction occurred only very close to the bed at z < 4 cm), however in-canopy flow reduction, has been observed in other seagrass meadows in the field (Verduin and Backhaus, 2000).

The present work presents and discusses results from a series of experiments performed in the CIEM (Canal d'Investigació i Experimentació Marítima) wave flume at the Universitat Politècnica de Catalunya, Barcelona, aimed at measuring wave energy dissipation over a full scale artificial *P. oceanica* meadow in shallow waters, as well as flow transformations. The experiments and the artificial plants have been described in detail by Stratigaki et al. (2009a, 2009b, 2011). Preliminary results indicated that the seagrass meadow reduced wave-induced flows and wave height and that the effect of the seagrass meadow was influenced by stem density (number of stems per square meter) and submergence ratios (the canopy height to water depth ratio, h_s/D), both under regular waves (Stratigaki et al., 2011) and irregular waves (Manca et al., 2010).

Those findings are integrated in the present work with those obtained from all tests, with a comparison of results from irregular and regular wave tests. In addition the present work has the following aims:

- (1) To relate wave energy reduction, expressed as wave energy dissipation factor and oscillatory flow dissipation within the lower canopy $(z/h_s=0.36)$, to wave conditions (wave orbital amplitude);
- (2) To investigate how friction over shallow submerged artificial *P. oceanica* relates to existing empirical models on friction over rough immobile beds;
- (3) To evaluate, from irregular wave tests, whether wave energy and flows are dissipated at a different rates at different components of the wave spectrum; and
- (4) To extend preliminary results on the effect of stem density and submergence ratio on flow and wave height attenuation by *P. oceanica* mimics.

These findings are discussed in terms of implications for nearshore sediments dynamics and hence beach protection by *P. oceanica* meadows.

2. Materials and methods

2.1. Experimental setup

The experiments were performed in the CIEM wave flume at the UPC in Barcelona, Spain. The flume is 100 m long, 5 m deep and 3 m wide (Fig. 1). Waves are generated by a wedge type paddle controlled by a computer using an active wave absorption system designed to limit wave reflection and seiching within the flume. A sandy slope, with a gradient of 1/15, was built at the opposite end of the flume to the wave paddle to further reduce wave reflection. Wave reflection analysis was performed to estimate reflection coefficients within the flume using the method of Mansard and Funke (1980). Reflection induced by the flume was on average less than 10% over all tests. As this value is relatively small, the effects of wave reflection on the result can be considered negligible.

A 20 m long flat sandy region was created in the central part of the flume and covered with a 0.7 m thick sand layer (Stratigaki et al., 2011). The meadow of artificial *P. oceanica*, was 2 m wide and 10.7 m in length (L) and the front of the seagrass meadow was located 38.36 m from the wave paddle in the flat central area (Fig. 1 and Fig. 2). The seagrass patch was built as a series of modules on boards that were fixed firmly together. A gap between the flume walls and the patch was created to avoid any disruptions to the movement of the mimics (Fonseca and Koehl, 2006). This also provided a better representation of the patchy seagrass distribution (Fonseca and Koehl, 2006), which is common in shallow water (Buia et al., 2004).

2.1.1. Posidonia seagrass mimics

The full-scale seagrass mimics were made of polypropylene strips, carefully designed to re-produce the flexibility and buoyancy properties typical of the natural *P. oceanica* plants. Scaling formulae involving the modulus of elasticity of the leaf materials were used to compare stiffness of natural leaves to the artificial blade stiffness, as a first indication in the selection of the plastic material for the construction of the plants. The physical properties of the *P. oceanica* leaves, with those of the PVC foam strips are compared in Table 3 (more details in Stratigaki et al., 2011). The *P. oceanica* plant has ribbon-like leaves, 1 cm wide and a maximum of 75 cm long (Borum et al., 2004; Buia et al., 2004) and is attached to a system of rhizomes, a type of modified stalk.

To simulate the plant morphology, each mimic was a composite of four blades of two lengths (one pair of 35 cm and a pair of 55 cm leaves, see Fig. 3b of Stratigaki et al., 2011). The dual leaf length was selected to reproduce the natural variation of the canopy biomass with height. Mimics with this variable leaf length were found to better simulate the oscillation and morphology of *P. oceanica*. in preliminary laboratory tests in wave flume (Manca. 2010) and unidirectional flow flumes (Folkard, 2005: Maltese et al., 2007). The leaves were inserted into a stiff 10.0 cm long rod. made of PVC, and introduced into perforated metal board and covered with about 2 cm to 4 cm of sand. About 4 cm of the rod was protruding from the sandy bed, to simulate the stiff rhizome of the plant. The canopy reached a maximum elevation of 55 cm from the sandy bed, when not exposed to waves, lying within the range of natural values of *Posidonia* canopy height (Gobert et al., 2006). The mimics reproduced the typical "whip-like" movement of seagrass plants under waves during the full-scale experiments in the CIEM flume, as also observed in the field and reported in literature (Bradley and Houser, 2009; Ghisalberti and Nepf, 2002)

2.1.2. Instrumentation and test conditions

Wave transformation was monitored by 14 pre-calibrated twin wire resistive wave gauges (WG) distributed along the flume at x/L = -0.05, 0.05, 0.14, 0.23, 0.42, 0.61, 0.79, 0.98, 1.17 (Fig. 1). Eight Acoustic Doppler Velocimeters (ADV) and four Electromagnetic Current Meters (EMCM) measured flow velocity and were arranged in three vertical profiles: Profile 0, in front of the meadow at x/L = -0.07 (where *x* is the distance along the flume from the leading edge of the meadow); Profile 1 within the canopy at x/L = 0.17; and Profile 2 at x/L = 0.80 within the canopy, closer to the trailing end of the meadow. Velocity measurements were taken at 4 different elevations from the flume bed (20 cm, 40 cm, 60 cm and 80 cm). Electro magnetic current meters were used for the measurements within the canopy at Profiles 1 and 2, ADV were used elsewhere (see Fig. 1). Electromagnetic current



Fig. 1. The artificial *P. oceanica* meadow within the flume with a meadow length L=10.70 m, seagrass height $h_s=0.55$ m, variable water depth D=1.10 m, 1.30 m, 1.70 m. The locations of the instrumentation used are also indicated. The origin of the *x'* coordinate used to indicate distances along the flume was at the wave paddle at rest (positive towards the shoreline). To define the locations of the instruments along the seagrass, a second coordinate system was used (*x*) where x=x'+38.36 m, (positive towards the shoreline). The wave gauge Wg12 was not in use.

meters measure the flow velocity by generating a magnetic field and measuring the potential differences in this field induced by ionized water particles passing through it. The *Posidonia* mimic blades are made of a non-conductive material and should not induce any variation in the EMCM induced magnetic field. The raw velocity time series, obtained from EMCM under regular waves, are characterised by a sinusoidal-like signal, as observed at Profile 0, and do not show any deviation or spikes that would indicate interference of the seagrass mimic blades near the sensor. Seventy-five tests with both regular (Table 1) and irregular waves (Table 2) were performed and analysed with wave heights and periods commonly observed in the Mediterranean Sea (Franco et al., 2004) and measured in the field over a shallow *P. oceanica* bed (Manca, 2010). For irregular wave tests, Jonswap spectra with a peak enhancement factor (γ) of 3.3 were produced. Water depth was varied between 1.1 m and 1.7 m (at the seagrass patch) to obtain four different submergence ratios (the canopy height to water depth ratio, h_s/D , see Table 1 and 2) and two different plant densities (360 and 180 stems/m² in staggered and



Fig. 2. The artificial seagrass meadow in the CIEM flume during the setup of the experiments.



Fig. 3. Decomposition of the original flow spectra into its wave-induced and "turbulent" components, in the region above the canopy (solid line, $z/h_s = 1.45$) and within the canopy (dashed line, $z/h_s = 0.36$): (a) The original flow spectra from the measured velocity time-series; (b) The spectra of the wave-induced velocity; and (c) The spectra of the remaining "turbulent" component (note the different scales of the vertical axes). Test 43, at x/L = -0.07 (Tp = 3.2 s, $H_0 = 0.33$ m, $h_s/D = 0.5$ and 360 stems/m²).

Table 1

Test conditions (regular waves) and measured wave parameters at x/L = -0.046, Tests c1 to c4 are the control tests, performed without the seagrass mimics.

Test	Stem density (stems/m ²)	Depth D (m)	Submergence ratio <i>h_s/D</i> (–)	Wave period T_p (s)	Wave number k ₀ (—)	Wave height H ₀ (m)	Wave length λ (m)	Wave-induced flow at $z/h_s = 0.36 U_{rms}^0$ (m/s)
1	360	1.70	0.32	3.00	0.59	0.40	10.69	0.26
2	360	1.70	0.32	4.00	0.41	0.46	15.16	0.29
5	360	1.70	0.32	2.00	1.06	0.38	5.93	0.16
19	360	1.50	0.37	2.00	1.09	0.36	5.79	0.18
21	360	1.50	0.37	3.50	0.51	0.44	12.32	0.37
22	360	1.50	0.37	4.00	0.44	0.43	14.39	0.34
23	360	1.50	0.37	3.00	0.62	0.36	10.20	0.28
24	360	1.50	0.37	4.00	0.44	0.35	14.39	0.26
29	360	1.30	0.42	2.00	1.12	0.38	5.60	0.22
30	360	1.30	0.42	2.99	0.65	0.32	9.65	0.28
31	360	1.30	0.42	3.00	0.65	0.43	9.67	0.35
33	360	1.30	0.42	3.50	0.54	0.46	11.62	0.39
34	360	1.30	0.42	4.01	0.46	0.42	13.54	0.36
36	360	1.10	0.50	2.00	1.17	0.42	5.36	0.27
37	360	1 10	0.50	3.00	0.70	0.34	9.03	0.32
38	360	1 10	0.50	3.00	0.70	0.45	9.03	0.38
39	360	1 10	0.50	4 01	0.50	0.40	12.56	0.32
40	360	1 10	0.50	3 50	0.58	0.48	10.81	0.39
41	360	1.10	0.50	4.02	0.50	0.48	12.61	0.39
48	180	1.10	0.30	2.00	1.06	0.38	5.91	0.16
10	180	1.70	0.32	2.00	0.50	0.30	10.66	0.22
4 <i>5</i>	180	1.70	0.32	2.55	0.55	0.57	10.00	0.22
51	180	1.70	0.32	2.00	0.39	0.40	15.05	0.20
52	180	1.70	0.32	2.59	0.41	0.40	12.13	0.27
52	180	1.70	0.32	4.00	0.45	0.40	15.17	0.50
55	180	1.70	0.32	4.00	0.41	0.47	7.20	0.23
54	180	1.70	0.32	2.50	1.00	0.39	7.59	0.23
67	180	1.50	0.37	2.00	1.09	0.35	5.79	0.19
68	180	1.50	0.37	3.00	0.61	0.35	10.22	0.24
69 70	180	1.50	0.37	3.00	0.62	0.40	10.21	0.31
70	180	1.50	0.37	4.00	0.44	0.38	14.40	0.25
71	180	1.50	0.37	3.50	0.51	0.44	12.32	0.38
72	180	1.50	0.37	3.99	0.44	0.44	14.34	0.33
/5	180	1.30	0.42	2.01	1.12	0.38	5.62	0.22
/6	180	1.30	0.42	3.00	0.65	0.31	9.66	0.28
//	180	1.30	0.42	3.00	0.65	0.40	9.67	0.35
78	180	1.30	0.42	4.01	0.46	0.31	13.54	0.30
79	180	1.30	0.42	3.50	0.54	0.51	11.60	0.39
80	180	1.30	0.42	4.00	0.47	0.41	13.49	0.37
81	180	1.30	0.42	2.30	0.92	0.39	6.84	0.31
93	180	1.10	0.50	2.00	1.17	0.38	5.35	0.27
94	180	1.10	0.50	3.00	0.69	0.33	9.05	0.32
95	180	1.10	0.50	3.00	0.70	0.42	9.04	0.39
96	180	1.10	0.50	3.99	0.50	0.33	12.51	0.33
97	180	1.10	0.50	3.49	0.58	0.46	10.79	0.39
98	180	1.10	0.50	4.01	0.50	0.42	12.56	0.40
99	180	1.10	0.50	2.30	0.97	0.42	6.50	0.34
100	180	1.10	0.50	2.00	1.17	0.41	5.36	0.26
c1	0	1.8	na	3	0.58	0.32	10.91	na
c2	0	1.8	na	3	0.58	0.40	10.91	na
c3	0	1.8	na	3	0.58	0.40	10.91	na
c4	0	1.8	na	3	0.58	0.33	10.91	na

non-staggered configuration, respectively) were tested. In natural *P. oceanica* beds, the stem density is variable, (number of stems per squared meter) ranging from 150 to over 700 stems/m², depending upon depth and health of the meadow (Buia et al., 2004; Gobert et al., 2006). The densities chosen are representatives of sparse and very sparse shallow meadows according to Giraud's (1977) classification of *P. oceanica* meadows.

2.2. Data analysis

2.2.1. Wave height decay and wave energy dissipation factors

For regular wave tests a zero-crossing method was used to calculate the significant wave height (H) and the peak wave period (T_p) from each water oscillation time series.

For irregular waves, wave heights from each wave gauge were obtained from wave spectra. Wave spectral densities (S_j) were estimated from the water surface elevation time series $(\xi(t))$ with

the classic Fast Fourier Transform (FFT), by applying a Welch's modified periodogram approach. The zero-moment wave height (H), for irregular waves, was estimated from the wave spectra (up to 1 Hz) at several locations along the artificial seagrass meadow:

$$H = 4\sqrt{\int_{j=0}^{j=n} S_j \Delta f_b}$$
(3)

where *n* is the number of frequency components and Δf_b is the frequency bandwidth (0.039 Hz).

In all tests the wave height decay along the flume was obtained by normalizing the measured wave height *H* to the wave height H_0 measured in front of the meadow (at x/L = -0.046). The wave height decay coefficient (K_i) was calculated using Eq. (1).

The friction induced by the artificial seagrass meadow was also evaluated in terms of a dimensionless parameter, commonly used

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Test conditions (irregular waves) and measured wave parameters at x/L = -0.046.

Test	Stem density (stems/m ²)	Depth D (m)	Submergence ratio <i>h_s/D</i> (–)	Wave period T ₀ (s)	Wave number k ₀ (—)	Wave height H ₀ (m)	Wave length λ (m)	Wave-induced flow at <i>z/h_s</i> =0.36 <i>U</i> ^o _r (m/s)
9	360	1.7	0.32	1.97	1.09	0.22	5.77	0.08
10	360	1.7	0.32	3.20	0.54	0.33	11.61	0.20
14	360	1.5	0.37	1.97	1.11	0.23	5.64	0.09
16	360	1.5	0.37	3.20	0.57	0.34	11.07	0.22
17	360	1.5	0.37	3.66	0.48	0.30	12.98	0.21
18	360	1.5	0.37	4.27	0.41	0.27	15.47	0.20
25	360	1.3	0.42	1.97	1.15	0.22	5.47	0.11
26	360	1.3	0.42	3.20	0.60	0.32	10.45	0.25
27	360	1.3	0.42	3.66	0.51	0.29	12.21	0.24
42	360	1.1	0.50	1.97	1.20	0.22	5.24	0.14
43	360	1.1	0.50	3.20	0.64	0.33	9.76	0.28
44	360	1.1	0.50	3.66	0.55	0.30	11.35	0.26
55	180	1.7	0.32	1.97	1.09	0.22	5.77	0.08
56	180	1.7	0.32	3.20	0.54	0.34	11.61	0.20
57	180	1.7	0.32	3.66	0.46	0.30	13.66	0.20
59	180	1.7	0.32	2.33	0.84	0.25	7.52	0.11
61	180	1.5	0.37	1.97	1.11	0.22	5.64	0.09
63	180	1.5	0.37	3.20	0.57	0.33	11.07	0.22
64	180	1.5	0.37	3.66	0.48	0.29	12.98	0.21
65	180	1.5	0.37	4.27	0.41	0.26	15.47	0.20
66	180	1.5	0.37	2.33	0.86	0.25	7.27	0.13
82	180	1.3	0.42	2.13	1.02	0.21	6.16	0.11
83	180	1.3	0.42	3.20	0.60	0.32	10.45	0.25
86	180	1.3	0.42	2.56	0.79	0.24	7.92	0.15
88	180	1.1	0.50	1.97	1.20	0.21	5.24	0.13
89	180	1.1	0.50	3.20	0.64	0.31	9.76	0.28
90	180	1.1	0.50	3.66	0.55	0.28	11.35	0.26
92	180	1.1	0.50	2.13	1.07	0.24	5.87	0.18

Table 3

Properties of the PVC foam blades used in the construction of the mimics, compared with those of the natural *P. oceanica* seagrass from the literature.

Property	PVC foam blades	<i>P. oceanica</i> leaves (Folkard, 2005)
Modulus of elasticity (<i>E</i>) x 10^9 N^{-2}	0.9	0.41-0.53
Density of material ($ ho_s$) kg m ⁻³	550-700	800-1020
Thickness (1) mm	1	0.2
Width (b) cm	1.2	1

in nearshore models, the energy dissipation factor (f_e) . It was determined from the wave energy loss along the meadow, assuming exponential wave height decay.

For regular waves, the energy dissipation factor (f_e) was derived using the formula of Jonsson (1966)

$$f_e = \frac{3}{2\pi} \frac{\varepsilon_f}{\rho U_\infty^3} \tag{4}$$

where ρ is the water density and U_{∞} is the theoretical "free stream" velocity at the top of the canopy (*z*=60 cm), obtained from second order wave theory:

$$U_{\infty} = \frac{\pi H}{T} \frac{\cosh kz}{\sinh kD} \cos(kx - \omega t) + \frac{3}{16} \frac{H^2 \omega k \cosh 2kz}{\sinh^4 kD} \cos(kx - \omega t)$$
(5)

The term ε_f is the rate of energy dissipation per unit area, due to friction, obtained from the change in the wave energy flux with distance along the meadow.

$$\frac{\delta E C g}{\delta x} = -\varepsilon_f \tag{6}$$

where E is the wave energy density and Cg the group velocity, both obtained from second order wave theory:

$$C_g = \frac{1}{2}c \left[1 + \frac{2kD}{\sinh(2kD)} \right]$$
(7)

$$E = \frac{1}{8}\rho g H^2 \tag{8}$$

where *c* is the wave celerity; *D* is the water depth; *k* the wave number, ρ the water density and *H* the wave height.

For irregular waves the representative wave energy dissipation factors $(f_{e,r})$ were calculated at the peak frequency from the wave energy decay using the same method as described for regular waves. This approximation appeared acceptable as most of the wave energy was lost at the peak frequency (as presented in the Results section).

2.2.2. Frequency-dependent wave energy dissipation factors

Since wave energy can be dissipated at different rates amongst the different spectral components (Madsen, 1994), wave energy dissipation was investigated at all components of the wave spectra following Madsen et al. (1988) approach. This method has been successfully used in the field and in flume tests over rigid and rough, submerged canopies (Lowe et al., 2005a, 2007). Assuming that all waves of all frequencies propagate in the same direction along the flume, the wave energy dissipation rate per unit area ($\varepsilon_{f,j}$) for the *j*th component of the wave spectra is equal to:

$$\frac{\Delta F_j}{\Delta x} = -\varepsilon_{f,j} \tag{9}$$

where Δx is the distance between the wave gauges and F_j is the *j*th component of the wave energy flux obtained from

$$F_j = E_j C g_j \tag{10}$$

where E_i is the component of the wave energy density

$$E_j = \frac{1}{2}\rho g a_j^2 \tag{11}$$

and Cg_i is the group velocity component obtained assuming:

$$Cg_{j} = \frac{1}{2} \frac{\omega_{j}}{k_{j}} \left[1 + \frac{2k_{j}D}{\sinh 2k_{j}D} \right]$$
(12)

with ω_j the radian frequency $(2\pi f_j)$ and k_j the wavenumber $(2\pi/\lambda_j)$ at the *j*th frequency component. The wave amplitude for each frequency (a_j) was calculated from the wave spectral densities (S_j) using:

$$a_j = \sqrt{2S_j \Delta f_b} \tag{13}$$

where Δf_b is the discrete frequency bandwidth. Each spectral component of the wave energy dissipation factor $(f_{e,j})$ can be obtained from the component of the rate of energy dissipation $\varepsilon_{f,j}$ as:

$$f_{ej} = \frac{4\varepsilon_{fj}}{\rho U_j^2 U_r} \tag{14}$$

with U_j the frequency-dependent horizontal wave-induced velocity calculated from the local wave spectra as:

$$U_j = \frac{a_j 2\pi}{T_j \sinh k_j D} \tag{15}$$

where T_j is the period of the *j*th component of the spectrum. The velocity magnitude was obtained from linear interpolation between two consecutive points of measurement, at z=60 cm. Eq. (15) assumes linear wave theory to be valid. The representative wave-induced velocity, U_r , was calculated, from the local wave spectral densities S_j and defined as:

$$U_r = \sqrt{2} \sqrt{\sum_j \left(S_j \Delta f_b \frac{4\pi^2}{T_j \sinh^2 k_j D} \right)}$$
(16)

2.2.3. Wave-induced flow dissipation

The measured velocity time series $(U_{inst}(t))$ were quality checked and de-spiked, using the phase-space method (Goring and Nikora, 2002) by removing the mean value $(U_m, defined as the$ $average value of <math>U_{inst}(t)$). The de-meaned measured horizontal velocity time series can be expressed as a sum of the waveinduced flows and the random turbulent fluctuations:

$$U(t) = U_{inst}(t) - U_m = U_w(t) + U_T(t)$$
(17)

Under regular waves, the horizontal component of the oscillatory velocity was obtained by ensemble-averaging the de-meaned velocity data (*U*), over successive waves (Pedersen et al., 1998):

$$\langle U \rangle = \frac{1}{N} \sum_{i=1}^{N} U(\omega(t + (i-1)T))$$
(18)

where ω is the radian frequency, *t* is time, *T* is the wave period and *N* the number of wave periods sampled. The root mean square value of $\langle U \rangle$ was calculated (U_{rms}) and used, in preference to the maximum value, so that results from both regular and irregular tests could be compared. In order to quantify the changes in the horizontal component of the wave-induced flow, induced by the artificial seagrass meadow, the velocities measured at Profile 1 and Profile 2 were normalised against the velocities measured at Profile 0 (U_{rms}^0) at the same elevation (in the lower canopy, at $z/h_s=0.36$); thus resulting in a dimensionless parameter α (hereafter referred to as the flow attenuation parameter), defined as:

$$\alpha = \frac{U_{rms}}{U_{rms}^0} \tag{19}$$

For irregular wave tests the Benilov and Filyushkin's (1970) method was used to separate $U_w(t)$, the wave-induced flow, from the total de-meaned velocity signal (U(t)). The de-meaned measured horizontal velocity time-series (U(t)) can be expressed as the sum of random turbulent fluctuations and the wave-induced flows (Benilov and Filyushkin, 1970). This method is based upon the concept that the signal $U_w(t)$ is highly correlated to the instantaneous free-surface displacement ($\xi(t)$), whilst the random fluctuations $U_T(t)$ are not correlated to $\xi(t)$ and are taken as the turbulent component of the flow (although they also contain some noise induced by the measuring methods). The wave-induced velocity spectral densities (SU_j) were calculated for all tests, at all elevations and profile locations, in front of and along the meadow. An example of the application of this method is shown in Fig. 3.

2.2.4. Frequency dependent wave-induced flow dissipation

An attenuation parameter was calculated (α_j) for each frequency component of the spectrum (Eq. (20) below), to evaluate the frequency-dependent changes in the flow induced by the canopy.

$$\alpha_j = \frac{SU_j}{SU_i^0} \tag{20}$$

where SU_j is the spectral density of the wave-induced velocity; and SU_j^0 is the spectral density of the wave-induced velocity in front of the leading edge of the meadow, both measured at $z=20 \text{ cm} (z/h_s=0.36)$. The attenuation parameter α_j was obtained both at Profile 1 and Profile 2.

The frequency range of the raw data was 0 to 10 Hz, however for the analysis of the wave-induced flows only the spectral frequencies containing most of the wave energy (95%) were considered. Considering all of the tests, the analysed frequencies ranged between 0.156 Hz and 0.70 Hz, corresponding to a range of wave periods, from 1.4 s to 6.4 s.

A representative value of the spectral orbital velocities (U_r) was obtained, by summing the contributions of each frequency component of the wave-induced velocity spectra (SU_j) . It corresponds to the RMS value of the measured wave-induced velocity time-series (Wiberg and Sherwood, 2008). A representative flow attenuation coefficient, for irregular wave tests, was obtained by normalising U_r against the value measured in front of the leading edge of the meadow at the same elevation, U_r^0 :

$$\alpha_r = \frac{U_r}{U_r^0} \tag{21}$$

3. Results

3.1. Wave height decay and energy dissipation

3.1.1. Wave height decay

Wave height reduction (H/H_0) along the artificial seagrass meadow was significant for all of the tests, with both regular (See also Stratigaki et al., 2011) and irregular waves, with wave height decreasing with distance along the meadow.

Wave energy loss induced by the walls and bed of the flume contributes to the wave height decay measured at the meadow and was estimated from previous experiments undertaken in the CIEM flume with the same seabed profile and sand grain-size. An example is shown in Fig. 4, where the wave height variation (H/H_0) , with distance *x* along the flat bed section of the flume,



Fig. 4. Example of wave height decay along the flat bed section of the flume. Four control tests were performed in the flume over a flat sandy bed without the seagrass meadow with regular waves in a water depth D=1.8 m (see Table 1). The H/H_0 was obtained as an average value of the tests. Wave height decay for two tests with *Posidonia* mimics performed in similar conditions are compared: Tests 1 with 360 stems/m² and Test 49 with 180 stems/m². The error bars at each data point correspond to the uncertainties in the measurement of H/H_0 . For the control tests error bars also include the standard deviation of the mean H/H_0 .

resulting from two experiments with the seagrass meadow (with 360 and 180 stems/m²) is compared with similar experiments (with the same seabed profile and regular waves T=3 s H=0.4 m D=2.5 m) without the seagrass meadow. The wave height variation in the control tests over a 10.7 m long flat sandy surface without the seagrass mimics was negligible (H/H_0) varying between 0.99 and 1) compared to the wave height decay measured over the same distance above the seagrass meadow $(H/H_0$ varying between 0.75 and 0.92). On average the wave height difference $(H-H_0)$ with x was about two orders of magnitude smaller over a sandy bed (with a mean value of -8×10^{-4}) than the decay measured above the meadow with a similar water depth $(-1.40 \times 10^{-2} \text{ on average for test with 360 stems/m}^2$ and -1.04×10^{-2} average for 180 stems/m² tests), therefore most of the wave attenuation can be attributed to the presence of the canopy. This is consistent with other studies (Asano et al., 1992; Kobayashi et al., 1993; Mendez and Losada, 2004; Nepf, 1999).

In many tests, both under regular and irregular waves, wave height increased at the edge of the meadow before decreasing. The tests with the densest canopy and the highest submergence ratio (h_s /D) showed the greatest wave height reduction.

The wave height decay H/H_0 was calculated for all tests and fitted (least square fit), to an exponential decay model (Eq. (1)) to obtain K_i , the wave decay coefficient. The goodness of fit was indicated by the R^2 (the ratio of the sum of squares of the regression and the total sum of squares of the errors, with a confidence level of 95%) and by the p value (p) of the fit. Only tests with p < 0.05 were selected, corresponding to R^2 larger than 0.45 (about 70% of the tests). The uncertainty for K_i is given as \pm the 95% confidence intervals of the fit in Tables A1 and A2 (which also give the root mean square error of the residuals, p values and R^2 of the fit). In some of the tests, the natural wave height modulation recorded along the meadow was large producing a poor fit to the exponential function, as found in other similar datasets and attributed to wave reflection by the meadow (Mendez and Losada, 2004). Tests having a low value of R^2 were not associated with a particular wave conditions or submergence ratio.

For irregular waves, the exponential wave height decay coefficient (K_i) ranged between 0.004 m⁻¹ and 0.025 m⁻¹. It was larger for the tests with 360 stems/m² (the average K_i =0.016 m⁻¹), than for the tests with 180 stems/m² (the average K_i =0.007 m⁻¹), particularly at high submergence ratios. Moreover, K_i increased with increasing submergence ratio and wave period for both stem densities (see Fig. 5a).

For regular waves, the coefficient K_i varied amongst the tests (Fig. 5b, K_i ranged between 0.09 m⁻¹ and 0.035 m⁻¹) and it was on average larger for tests with 360 stems/m² (average K_i =0.015 m⁻¹) than for tests with180 stems/m² (average K_i =0.007 m⁻¹). Generally, under regular waves, the same trends as for irregular wave tests were observed, however the effect of wave period on wave height decay was not as clear.

3.1.2. Wave energy dissipation factors and roughness

For each test energy dissipation factors were calculated from the wave height decay data (using Eq. (4)) as averages from the values obtained for each pair of consecutive wave gauges along the meadow ($\overline{f_e}$ and $\overline{f_{e,r}}$ for irregular waves). As the standard deviation was large, the wave energy dissipation factor was also calculated from wave height values obtained by applying the exponential decay model (Eq. (1)), for those tests which showed a good fit. These modelled factors (f_e and $f_{e,r}$) were plotted against the factors calculated from the data $\overline{f_e}$ (and $\overline{f_{e,r}}$). The correlation obtained was good (R^2 =0.87).

Values of f_e obtained from the regular tests varied between 0.03 and 0.59 with an average of 0.16 and 0.09 for high and low stem densities, respectively. The f_e values were found to decay with increasing wave orbital amplitude (Fig. 6a). The wave orbital amplitude was obtained using

$$A = U_{\infty} T_p / 2\pi \tag{22}$$

with U_{∞} the theoretical "free stream" velocity at the canopy top (defined as in Section 2.3.1), and T_p the peak wave period).

$$Re_w = AU_{\infty}/v \tag{23}$$

The wave Reynolds number was computed from

with *v* the kinematic viscosity of water.

In particular, the energy dissipation factor decayed with increasing wave orbital amplitude, A, for both densities; the values were lower for the same A, when the stem density was 180 stems/m² (Fig. 6a).

The values of f_e measured in the flume were compared to Eq. (2) assuming $f_e=f_w$. Tests with density 360 stems/m² showed a very good fit ($R^2=0.91$) to Nielsen's (1992) formula. The hydraulic roughness (r) that provided the best fit with these data was 0.08 m (henceforth known as r_{360}). Similarly f_e data from the low density meadow (180 stems/m²) also produced a good fit with Nielsen equation ($R^2=0.68$) when r=0.03 m (henceforth known as r_{180}).

Under irregular waves, representative wave energy dissipation factors ($f_{e,r}$) (Fig. 6b), calculated at the peak frequency of the spectra, varied between 0.11 and 0.26 amongst the tests with a good fit to the exponential decay model. These values are close to values obtained for regular wave tests except for those tests with A < 0.1 m and very small wave Reynolds numbers.

3.1.3. Frequency-dependent wave energy dissipation factors

The frequency-dependent wave energy dissipation factor $(f_{e,i})$ was calculated for all of the tests, between the site in front of the leading edge of the seagrass meadow (at Profile 0) and the site over the meadow nearest to its leading edge (Profile 1). It was also calculated between Profile 1 and the site further into the meadow at Profile 2 (see an example in Fig. 7). The largest values of $f_{e,j}$ were always associated with the site located nearest to the



Fig. 5. Effect of submergence ratio (h_s/D) and stem density on the wave height decay coefficient (K_i) for density = 360 stems/m² (solid symbols) and density = 180 stems/m² (open symbols). Different symbol types represent different wave periods. (a) Irregular wave tests. (b) Regular wave tests.

leading edge: on average over all tests $f_{e,j}$ was 0.12 ± 0.066 between Profile 0 and Profile 1 and it was 0.05 ± 0.065 between Profile 1 and Profile 2. Therefore, most wave energy was dissipated in the first few metres of the meadow. In all tests $f_{e,j}$ was largest around the peak frequencies of the wave energy spectrum.

3.2. Wave-induced flow dissipation

The velocity data (expressed as U_{max} , the peak value of $\langle U \rangle$) were compared to theoretical values to evaluate the methodology; and to ensure that the data at the control profile (Profile 0) were not affected by the presence of the meadow.

Linear wave theory, with small U_{max} , produced a good fit with the wave-induced flow data measured outside the meadow. However, a better fit for the range of U_{max} was found when velocities were predicted using Stokes second order theory (Fig. 8). As the velocities followed second order wave theory, it was concluded that, in front of the meadow (at Profile 0), they were not significantly affected by the presence of the meadow. As wave reflection was similar, in both regular and irregular wave datasets, it can be assumed that the velocities measured outside the meadow for the irregular tests were also not affected by the presence of the meadow. The repeatability of the tests was evaluated by comparing the velocities measured at the control



Fig. 6. Wave energy dissipation factors plotted against the wave orbital amplitude (*A*) for the two stem densities. Data from tests with a reliable wave height exponential decay fit (*p* value < 0.05) are shown. (a) Regular wave tests: wave energy dissipation factors (f_e). (b) Irregular wave tests: representative wave energy dissipation factors ($f_{e,r}$). In both graphs (a) and (b) the same models obtained by fitting Nielsen's (1992) formula (Eq. (2)) to the regular wave data are overlaid. The solid line is used for tests with a stem density of 360 stems/m² and produced a "best fit" when the hydraulic roughness (r) was 0.08 m. The dashed line is used for tests with a stem density of 180 stems/m² with r=0.03 m.

site for different stem densities. An average difference of 1 cm/s (2.89% of the velocity magnitude) was found for the *U* component. The differences between the measured data at the meadow (Profiles 1 and 2) and those at the control profile (Profile 0) were significantly greater than the natural variability in the experiments.

were not used as the velocities measured at Profile 0 may have been affected by the presence of the meadow (or require the application of a higher-order theory).

The results presented are based on data from all irregular wave tests and from 81% of the regular wave tests: the remaining tests

3.2.1. In-canopy wave-induced flow dissipation

The wave-induced flow attenuation parameter (α), expressing the changes in the horizontal component of the wave-induced



Fig. 7. (a) Wave energy density spectra at x/L = -0.07 (Profile 0), x/L = 0.17 (Profile 1) and x/L = 0.80 (Profile 2). (b) The difference in the frequency-dependent wave energy dissipation factor ($f_{c,j}$) calculated between Profile 0 and Profile 1 (squares) and between Profile 1 and Profile 2, (diamonds), plotted at each component of the spectra. Test 42 ($T_p = 1.98$ s, $H_0 = 0.22$ m, $h_s/D = 0.50$ and 360 stems/m²).



Fig. 8. U_{max} measured at Profile 0 for regular wave tests plotted against the predicted value of U_{max} obtained using linear theory (full circles) and Stoke's second-order theory (empty circles).

flow provoked by the seagrass meadow, was calculated both at both profiles (1 and 2), using Eq. (19).

For regular waves the percentage reduction of U_{rms} in the lower canopy (i.e., $100(1-\alpha)$), with 0% corresponding to no velocity reduction) within the seagrass meadow (Profile 2) was always larger than near the edge of the meadow (58.7% at Profile 2 and 12.1% at Profile 1 for the higher density meadow tests). On average at Profile 2 the wave-induced flow reduction was 3% larger for the tests with 360 stems/m² density than those with 180 stems/m², and it was more significant (8%) at the edge of the meadow (Profile 1). At Profile 2 the variation amongst all tests



Fig. 9. In-canopy flow attenuation parameter for regular waves (α) and irregular waves (representative value, $\alpha_{,r}$), plotted against the ratio of wave orbital amplitude (A) to stem spacing (S), both at Profile 1 (x/L=0.17) and at Profile 2 (x/L=0.80).

was only 5–5.7%, whilst at (Profile 1) it was larger therefore depending greatly on the wave conditions tested.

The wave-induced flow attenuation parameter (α), varied between 0.66 \pm 0.05 and 1.12 \pm 0.03 at Profile 1 and 0.33 \pm 0.03 and 0.54 \pm 0.01 at Profile 2. On average the uncertainty associated with α was 3.0% of the value at Profile 1 and 3.8% at Profile 2. At both densities α decreased with increasing *A*, indicating that the horizontal component of the in-canopy flow was reduced more by the waves characterised by large orbital amplitudes.

The representative oscillatory velocity of irregular waves U_r , obtained from Eq. (16), was normalised against the corresponding value measured in front of the meadow to obtain an attenuation parameter α_r (as in Eq. (21)). Both α_r and α were plotted against the ratio A/S, where S is the stem spacing (Fig. 9). For the high-density, non-staggered configuration, the stem spacing was S_{360} =0.050 m;

whilst for the low-density staggered configuration it was different in the *x* and *y* directions $0.062 \text{ m} < S_{180} < 0.088 \text{ m}$, on average $S_{180} = 0.075 \text{ m}$. A large reduction in wave-induced flow ($\alpha_r < 1$) was measured at Profile 1 and the flow was further reduced at Profile 2. This was also observed for regular waves. However, some intensification in the lower canopy was observed, near the edge of the meadow (at Profile 1) for A/S < 2.5.

3.2.2. Frequency-dependent wave-induced flow dissipation

Wave-induced velocity spectral densities (SU_j) at the front of the artificial seagrass meadow (Profile 0) were compared with those measured at both locations within the meadow and a frequency-dependent wave-induced flow dissipation coefficient $(\alpha_{i}, \text{Eq. (20)})$ was obtained.

As an example, some spectra are shown in Fig. 10a, measured in front of the meadow (Profile 0), inside near the edge of the meadow (Profile 1) and further into the meadow (Profile 2). The corresponding frequency-dependent flow attenuation coefficients (α_i) are presented in Fig. 10b.

In all of the tests, α_j measured in the lower canopy decreased with the increasing period of the spectral component (T_j), at both locations within the meadow and for both meadow densities. At the edge of the meadow (Profile 1), the flows created by the short period components of the spectrum are enhanced ($\alpha_j > 1$). At this location, reduction occurs only for the components with a long period, whilst further inside the meadow (Profile 2) the wave-induced flow attenuation is significant for all periods (ranging between 0.4 and 0.1, depending upon the tests conditions).

The spectral attenuation coefficient at the components of the spectra with periods (T_j) smaller than 2 s is often significantly larger than 1.0 at Profile 1 (see for example Fig. 10b). The reasons for these occurrences are not clear. As this happens in all tests, it might be an artefact of the methods used. However, this should not be the case because in Manca et al. (2010) the data were analysed using a different method (which required linear wave theory to be valid even above the seagrass meadow) and the

results obtained were very similar: a decay of α_j with increasing T_j , and values of $\alpha_j > 1$ at the short period components. Moreover the same observations were made independently of the frequency bandwidth (Δf_b) used to compute the spectra. Similarly, flow intensification was measured for small values *A/S* (as reported in the previous section). Observed enhancement might be related to the increase in wave height near the canopy edge or to significant modifications of the boundary layer characteristics. However, the current dataset does not provide a satisfactory answer, and further experiments are required to better understand this phenomenon. The main trend of larger wave-induced flow reduction (decreasing α_j) with increasing wave period of the spectra component, can be considered significant, as it is consistent for all irregular wave tests, and is in line with the trends observed for regular waves (see Section 3.2.1).

The α_j was significantly less for all T_j components of the spectrum, for the tests having the lowest submergence ratio (Fig. 11). The largest α_j values always occurred in lower meadow densities, when the same wave spectra and depths were compared (Fig. 12). The effect of meadow density was significant at all water depths and also for the least energetic wave conditions. The divergence was greatest within the longer period components of the spectrum and at the edge of the meadow. These patterns are consistent with observations on the effect of density on flow reduction under regular waves (see Section 3.2.1).

4. Discussion

4.1. Wave height decay in shallow P oceanica

The *P. oceanica* mimics affected significantly the propagation of waves under all of the conditions tested. Most of wave height decay over a flat artificial seagrass bed, occurred within the first few metres of the meadow, for both regular and irregular waves. These findings are similar to earlier studies (Augustin et al., 2009;



Fig. 10. (a) Spectra of the wave-induced flows measured in the lower canopy at Profiles 0, Profiles 1 and 2 (x/L = -0.07, x/L = 0.17 and 0.80) along the flume. (b) The spectral attenuation parameter α_j (attenuation of flow at each period of the spectral component $1/f_j$); In the horizontal axis $T_j = 1/f_j$, with f_j the frequency of spectral component. The curves represent different locations along the flume. Test 26 of Table 2 ($T_p = 3.2$ s, $H_0 = 0.32$ m, $h_s/D = 0.42$ and 360 stems/m²).



Fig. 11. Effect of submergence ratio $(h_s/D=0.37; 0.42; 0.50)$ on the spectral attenuation coefficient (α_j) , calculated for each wave period (T_j) of the wave-induced velocity spectra component. (a) The data at Profiles 1 (x/L=0.17). (b) The data at Profile 2 (x/L=0.80). Tests 16 $(h_s/D=0.37 \text{ and } H_0=0.34 \text{ m})$. Test 26 $(h_s/D=0.42 \text{ and } H_0=0.32 \text{ m})$ and Test 43 $(h_s/D=0.50 \text{ and } H_0=0.33 \text{ m})$. All tests were carried out with a stem density of 360 plants/m² and peak wave period of 3.2 s.



Fig. 12. Effect of plant density on the spectral attenuation coefficient (α_j) , calculated for each wave period (T_j) of the wave-induced velocity spectral component. (a) The data at Profiles 1 (x/L=0.17) (b). The data at Profile 2 (x/L=0.80). Tests 44 and 90 with $H_0=0.30$ m and $H_0=0.28$ m, respectively. Both test were carried out with $h_s/D=0.50$ and $T_p=3.7$ s.

Bradley and Houser, 2009; Kobayashi et al., 1993) on wavevegetation interaction. In some tests, wave height increased in the first metres of the meadow, before decaying due to frictional dissipation, as reported in preliminary results on regular wave tests (Stratigaki et al., 2011). This phenomenon has been recorded in natural shallow seagrass beds (Bradley and Houser, 2009) and it could be explained by local wave interaction (by reflection or diffraction) caused by the sudden change in bottom topography encountered by the waves.

Values of wave decay coefficients (K_i) for irregular waves (ranging between 0.004 m^{-1} and 0.025 m^{-1}) are comparable with values found for Thalassia testudinum dominated mixed seagrass beds in the field $(0.004-0.02 \text{ m}^{-1})$, Bradley and Houser, 2009) and with reported values of K_i in a British salt-marsh $(0.01 \text{ m}^{-1} \text{ Möller et al., 1999})$. Values of K_i for regular waves were generally larger (varying between 0.009 m^{-1} and 0.035 m^{-1}). A recent experiment using *P. oceanica* mimics at 1:10 scale (Sanchez-Gonzalez et al., 2011) found that K_i varied between 0.083 m⁻¹ and 0.192 m⁻¹ under regular waves and between 0.011 m^{-1} and 0.017 m^{-1} under random waves. To relate scale model results to natural full scale conditions, the application of the Froude similitude law is required. The Froude scaling is based upon the assumption that gravity is the main physical force balancing the inertial forces and that all other physical forces (such as viscosity and elasticity) are incorrectly scaled (Hughes, 1993). Other properties that might be important in vegetated beds, such as turbulence, or boundary layer processes are not considered in Froude scaling, therefore they might not be correctly represented in scaled tests.

4.2. Energy dissipation factors and hydraulic roughness in shallow P. oceanica

On sandy beds, friction factors depend, not only upon relative roughness, r/A (ratio of hydraulic roughness to wave orbital amplitude), but also upon the flow regime (indicated by the wave Reynolds number, Re_w) (Nielsen, 1992; Soulsby, 1997). The relationship of dissipation factors (f_e and $f_{e,r}$) to wave Reynolds number for artificial *P. oceanica* is shown in Fig. 13. Energy dissipation factor values depended on the flow conditions with the largest values which are associated with the least energetic wave conditions (see Fig. 13). In all conditions the data were above the theoretical wave energy dissipation factors values for



Fig. 13. Relationship between energy dissipation factors and wave Reynolds number. Data for *P. oceanica* tests for regular (f_e , empty symbols) and irregular waves (f_{er} , solid symbols). Squares stand for tests with 360 stems/m² and circles for 180 stems/m². Grey symbols represent data from a field study on *Z. noltii* seagrass-wave interactions by Paul and Amos (2011), under similar conditions. The solid line is the theoretical relationship for laminar flow conditions ($f_e=2/\sqrt{Re_w}$).

laminar flow regimes (solid line of Fig. 13, obtained from $f_e=2/\sqrt{Re_w}$), hence the flow regime was fully turbulent.

Modelled friction factors, for low density salt-marsh vegetation, ranged between 0.05 and 0.19 (Augustin et al., 2009) and between 0.07 and 0.38 in a natural salt-marsh (Möller et al., 1999). These values are in the lower part of the range of the values of f_e (and $f_{e,r}$) found in this study (between 0.03 and 0.59). However the capacity of submerged vegetation for attenuating wave energy varies with the meadow characteristics (Koch et al., 2009), and the hydrodynamic conditions (see Fig. 13 and Bradley and Houser, 2009: Paul and Amos, 2011). This makes the comparisons of results quite difficult. Under similar fully turbulent regimes, energy dissipation factors for *P. oceanica*, both under regular and irregular waves, are in the upper range of those measured above a natural Zostera noltii meadow (Paul and Amos, 2011). This result should be expected because Z. noltii, despite creating much denser meadows, has much more flexible and shorter leaves (around 13 cm, Paul and Amos, 2011) than those of P. oceanica, and variation in vegetation-induced wave attenuation is related to shoot stiffness (Bouma et al., 2005) and plant morphology (Koch et al., 2006b).

A clear decrease in the energy dissipation factor with an increase of the wave orbital amplitude over the patch of submerged vegetation (Fig. 6) emerges from this work, in agreement with earlier studies of wave dissipation over other rough seabeds such as coral, sandy and rippled beds; (Lowe et al., 2005a; Nielsen, 1992; Sleath, 1984; Soulsby and Clarke, 2005). Perhaps one of the most interesting findings of this study is that the dissipation factors varied predictably as a function of wave amplitude, following the classical Nielsen (1992) empirical model (Eq. (2)), which is valid for sandy and rippled beds in fully turbulent conditions. The best correlation coefficient of Eq. (2) was produced when the hydraulic roughness (r) was 0.08 m for a canopy density of 360 stems/m², and r=0.03 m for 180 stems/m². The hydraulic roughness length is commonly used in coastal modelling and provides a yard-stick to compare the roughness of sandy/rippled beds to those created by seagrass. The values of canopy hydraulic roughness are larger than typical values found for sandy beds, even though sparse and very sparse Posidonia meadows were simulated in this study. This confirms results for P. oceanica meadows under unidirectional flows (Gacia and Duarte, 2001).

Wave energy dissipation and roughness were larger for the denser canopy, than the less dense canopy. This occurred under both regular and irregular waves, in agreement with results from research on other types of vegetation (Bouma et al., 2005; Penning et al., 2009). Also in P. oceanica experiments the hydraulic roughness was a fraction of the canopy height ($r_{180}=0.06h_s$ and $r_{360}=0.15h_s$); and depended also upon the canopy density $(r_{360}=2.67r_{180})$ with very little dependence on submergence ratio. In natural mixed T. testudinum dominated seagrass beds, roughness varied between 0.03 m and 0.38 m (Bradley and Houser, 2009), which is between approximately 0.1 and 1.3 times the canopy height. In some studies the hydraulic roughness length has been related to a physical roughness. The Nielsen (1992) formula was derived for sandy beds, relating the r to the grain diameter (d_{50}) or with ripple length. With coral reefs (Lowe et al., 2005a), the hydraulic roughness was related to the physical elevation of roughness elements measured on the reef. However, these authors recognised that the hydraulic roughness depends often upon the spacing of the elements, their configuration as well as their height above the bed. The physical meaning of the hydraulic roughness for experiments with vegetation might be spurious (Bradley and Houser, 2009) and further field data are required to confirm these observations.

Representative energy dissipation factors ($f_{e,r}$), were close to those predicted by the Nielsen's (1992) empirical model (derived

from regular wave measurements, Fig. 6b). However, under very low energy conditions and irregular waves, the system appeared to behave in a different way. Low energy irregular waves ($Re_w < 1.8 \times 10^4$) were characterised by energy dissipation factors larger than those observed for more energetic tests (see Fig. 6b), but not as high as predicted by the Nielsen's (1992) model. The Nielsen (1992) model could not be applied to all flow regimes, and the dissipation factor might not increase as rapidly with decreasing Re_w . Another explanation might be that the mimics are responding to very small waves in a different way, for example, bending very little (as observed from a side window of the flume) or oscillating at a different frequency than the waves.

These findings also show the importance of large-scale flume experiments in understanding processes in vegetated beds: smallscale tests are unable to generate sufficiently large Reynolds numbers, to demonstrate the patterns of behaviour observed here.

The highest submergence ratios produced the greatest wave height decay along the meadow as observed in scaled model *P. oceanica* (Sanchez-Gonzalez et al., 2011). However, the changes in the submergence ratio (for a constant canopy height), on energy dissipation rates were not as significant compared to the effect of wave period and orbital amplitude (*A*) for the range of submergence ratios tested here (h_s/D between 0.32 and 0.5).

Irregular wave tests were also performed to examine wave attenuation at different parts of the wave spectra with period of the spectra components ranging between 1.4 s and 6.4 s, which can be considered typical of wind wave conditions in the coastal Mediterranean Sea (Franco et al., 2004). Values of the frequencydependent wave energy dissipation factor $(f_{e,j})$ were highest for the least energetic wave spectra and greatest at the peak frequency. These results are supported by field observations over natural mixed seagrasses under low wave energy conditions (Bradley and Houser, 2009) where longer period components of the wave spectra were not affected by the seagrass and that preferential dissipation occurred at the peak frequency (1.3 s). However in a study over a barrier reef, the largest wave energy dissipation corresponded to the high frequency part of the wave spectrum (sea and swell waves, with peak wave periods ranging between 7 s and 10 s) (Lowe et al., 2005a). Results from in-situ studies on saltmarshes are also contradictory: according to some the percentage of wave energy dissipation by the plants was largest for waves having the shortest period (Meijer, 2005), whilst other studies found that wave energy attenuation was not frequency-dependent (Möller et al., 1999). Because simple Jonswap spectra were created in the present study, with just one main peak, the range of periods observed was limited. For this reason, more work is required on frequency-dependent energy dissipation by seagrass meadows in the field and for spectral conditions characterised by longer wave periods.

4.3. In-canopy wave-induced flow dissipation

The wave-induced component of the flow was reduced inside the canopy and the reduction increased with increasing wave orbital amplitude *A* and stem density. Under irregular waves inside the canopy, the velocity reduction induced by the seagrass varied across the spectrum and attenuation was largest for the longest wave periods. This pattern has also been observed in other very rough beds (Lowe et al., 2005b), but never from data on flexible vegetation mimics, at full scale. Luhar et al. (2010), found in laboratory studies on mimics of *Z. marina*, very small reduction of wave-induced flows for values of A/S < 2 (wave orbital amplitude to stem spacing ratio) close to the inertial force dominated limit of A/S = 1 (Lowe et al., 2005b). However they recognised that a significant reduction of oscillatory flow might take place for large seagrass species (0.68 to 0.90 for *P. oceanica*) even close to the inertial limit.

According to Lowe et al. (2007) in canopies made of rigid elements, such as coral canopies, wave energy dissipation is closely linked to wave-induced flow dissipation. In their study it was found that with increasing wave orbital amplitude the friction exerted by the coral canopy was smallest whilst waveinduced flow reduction was largest, in agreement with the findings from the present work. The authors explain the phenomenon by arguing that oscillatory flows characterised by small orbits can penetrate deeper into the canopy than those with larger orbits, and therefore the latter are more reduced. As flow velocity under large orbital amplitude waves is reduced by the canopy, the frictional drag (which is proportional to the flow velocity) is also reduced. This explanation might be applicable to P. oceanica as the wave-induced flow reduction increased with increasing A/S, see Fig. 9), in the conditions tested (from inertial force dominated to general flow conditions, A/S between 0.5 and 11.7).

In the lower canopy, the wave-induced flow reduction from the free-stream was at least 5 times larger inside the meadow at Profile 2, than near the leading edge of the meadow. This observation demonstrates the importance of the "distance travelled" through the meadow in near-bed wave-induced flow attenuation. Under all conditions, wave-induced flow velocity at the leading edge of the meadow was greater than downstream, resulting in higher drag at the edge of the meadow and explaining the largest wave height reduction rates near its leading edge.

The denser seagrass meadow produced a greater waveinduced flow reduction in the lower canopy, at all wave amplitudes tested. This result is analogous to results from many studies on open channel flow or flows in current-dominated vegetated seabeds, where plant canopies with high stem density had a larger capacity to attenuate unidirectional flows (Gambi et al., 1990; Neumeier and Ciavola, 2004; Peralta et al., 2008). High submergence ratios (h_s/D) produced a larger attenuation of oscillatory flows in the lower canopy. This result is also in line with findings from unidirectional flow studies: the greater the proportion of the water column that the canopy occupies, the more effective it is at reducing unidirectional flows (Fonseca and Fisher, 1986; Thompson et al., 2004). Furthermore, in a natural *P. oceanica* meadow, an increase in canopy height (hence increase in submergence ratios, h_s/D , resulted in an increase in unidirectional current reduction (Gacia et al., 1999).

4.4. Implications for nearshore sediment dynamics

P. oceanica is capable of modifying its hydrodynamic environment creating a rough surface and causing wave energy dissipation, particularly for small-orbital amplitude waves and at low Reynolds numbers. Oscillatory velocities were also significantly affected, especially for long-period waves. These findings confirm that *P. oceanica* is able to shelter the seabed and help protect beaches from erosion.

P. oceanica reaches its maximum biomass in the summer and begins shedding its older leaves with the first autumn storms. Since the canopy height (and therefore, submergence ratios) varies over the year, the friction exerted by the canopy is likely to vary seasonally too, as found for *Z. noltii* (Paul and Amos, 2011), which dies back in winter and has large seasonal variations in plant density. The seasonal differences in biomass might not be as pronounced as for *Z. noltii*, however it is possible that *Posidonia* is more efficient at reducing wave energy during the summer months when its leaves are longer (Gobert et al., 2006) and the fair weather promotes small amplitude waves. In winter, with larger waves and reduced canopy biomass, the capacity of

enhancing friction at the bed is reduced. However, under these large waves, the plants are still capable of producing locallysheltered conditions, as they proved to be very efficient at reducing the wave-induced flow close to the bed therefore, reducing also shear stresses and stabilising locally the sediment. This could act against the loss of sediment far offshore during storms, maintaining beach sediment inshore. By maintaining a shallower water depth the meadow will also offer some additional protection to the landward profile by flattening the slope of the shoreface.

Hydraulic roughness might also be affected (probably increased) at large scale by the complex topography created by the meadows and at a small scale near the bed by the presence of roots and rhizomes of the plants and associated organisms, which could not be simulated in present laboratory experiments. In natural *P. oceanica* meadows these elements would be expected to contribute to trapping sediment.

Flow reduction, at all spectral components and for all conditions tested, was limited near the leading edge of the seagrass meadow. For this reason the trapping effects of *Posidonia* meadows are expected to be reduced at the edge of the meadows. This idea is supported by previous results on increased Reynolds stresses at the edge of a natural *P. oceanica* meadow (Granata et al., 2001). Increased sediment resuspension, instead of deposition, could take place at the edge of the meadows under waves, as takes place around saltmarshes (Feagin et al., 2009). Meadow size is thought to be an important factor when evaluating the capacity of a meadow to stabilise the seabed. Fragmentation of a meadow (created by scours due to anchors dragging on the seabed, for example) to a series of patches will reduce the capacity of the meadow to stabilise the bed and reduce wave energy.

5. Conclusions

The effect of *P. oceanica* in shallow water conditions on wave energy decay and wave-induced flow reduction in the lower canopy were investigated at full scale, testing several regular and irregular wave conditions. A number of conclusions can be drawn from this investigation:

- 1. Experiments under controlled wave conditions indicate that shallow *P. oceanica* meadows are effective at reducing wave energy, especially under low wave energy conditions and small wave amplitudes, under both regular and irregular waves.
- 2. Friction produced by submerged canopies under higher wave Reynolds number decay with wave amplitude and may be predicted by empirical formulae, such as the Nielsen (1992) model. For the range of Reynolds numbers tested under regular waves (Re_w between 3.2×10^4 and 5.3×10^5), canopy roughness (r) is only a function of the canopy characteristics, such as stem density and canopy height. Therefore, given the canopy characteristics and wave conditions (expressed by A, the wave orbital amplitude), wave friction factors (f_w) induced by *Posidonia* canopies in shallow waters might be predicted with this simple empirical relationship. Wave attenuation under irregular wave conditions (Jonswap spectra) by the artificial *P. oceanica* canopy occurs at all frequencies of the wave spectra, but mostly at the peak spectral frequency.
- 3. In the lower canopy in all conditions wave-induced flows are reduced compared to the velocity measured outside the seagrass patch, but especially under the largest waves. On average the reduction of the wave-induced flows was 12.1% near the seagrass leading edge (P1) and 58.7% further shoreward (P2). The longer period components of the wave-induced flow spectra are more attenuated than the shortest ones.

- 4. Increases in stem density, in the conditions tested, induced: greater wave attenuation and enhanced wave-induced flow deceleration. High submergence ratios (h_s/D) produced larger wave height reduction and flow reduction within the lower part of the canopy, closer to the sandy flume bottom
- 5. The flume results show that conditions at the edge of the canopy are more energetic and oscillatory flows are less reduced than further inside the meadow, where more uniform and stable hydrodynamic conditions prevail.
- 6. Under large waves, *P. oceanica* is less efficient at reducing wave energy; however, it is very efficient at reducing oscillatory flows near the bed, thereby locally reducing sediment transport. *P. oceanica* plants, probably, do not offer a noticeable protection of beaches from wave erosion during storms, but these results indicate that they are able to promote greater sediment stabilisation in the nearshore than unvegetated beds.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.csr.2012.10.008.

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