Spectral Wave Attenuation over *Posidonia Oceanica*

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Abstract: *Coastal vegetation, such as sea grasses has the following functions regarding hydrodynamic aspects; wave attenuation, protection of the hinterland from wave attack, stabilizing the seabed. In this work an experimental study on wave energy dissipation and velocity structure over Posidonia Oceanica is performed, with P. Oceanica being the most abundant sea grass species in the Mediterranean Sea. Large scale experiments have been conducted in the CIEM flume for irregular intermediate water waves, for the investigation of wave attenuation related to the seagrass characteristics. Results show the efficient wave height attenuation, ranging from 15%-30%, depending on the seagrass characteristics; the seagrass submergence ratio (*h_s/D*,* h_s*=seagrass height, D=water depth) and its density (stems/m*^{2}*). Wave attenuation increases with increasing plant density and submergence ratio and is obvious for all components of the wave spectra, especially at peak frequencies. Regarding the velocity field, it is shown that the velocities of the longer wave components are mostly attenuated compared to the short wave components. Also the results from the velocities measured at the edge of the seagrass meadow reveal the complicated velocity structure near the edge of the meadow, due to the nonlinear interaction of the wave motion and the movement of the leaves of the seagrasses.*

Keywords: *seagrasses, P. Oceanica, wave attenuation, wave-vegetation interaction.*

1. INTRODUCTION

The need for mitigation of flooding and/or erosion hazards with low environmental impact on the coastal environment, can be satisfied with the use of natural coastal defence "structures"; coastal benthic communities, such as salt marshes, coral reef and seagrass beds. Due to their capacity to alter their environment, seagrasses have been referred to as ecosystem engineers, because they partly create their own habitat: the leaves attenuate wave and current action increasing sedimentation, and the seagrass roots and rhizomes stabilize the seabed.

The most abundant seagrass species in the Mediterranean Sea is *Posidonia Oceanica*, which can colonize soft substrates such as sand in wave-sheltered areas and also attach to rocks being exposed to relatively high wave energy wind driven currents (Koch *et al*, 2006). *P. Oceanica* seagrass meadows are usually distributed in shallow areas from the surface to a depth of 30-40 m in clear conditions, while the plants density varies from sparse (<150 stems/m^2) found in deeper waters to dense (>700 stems/m^2). The plant has ribbon-like leaves, 1.0 cm wide and up to 1.0 m long.

With regard to the hydrodynamics, a complex water flow system describes the situation, since not only water flow affects seagrasses and seagrasses affect water flow but seagrasses and water flow may interact in highly coupled, nonlinear ways. This interaction of the water flow with the underwater vegetation is dynamic such that the structure of aquatic plant fields changes with time and is exposed to variable physical forcing of the water flow, such as wave breaking (Mendez and Losada, 2004). The degree of wave attenuation depends both on the seagrasses characteristics (the seagrass density, the canopy height, the stiffness of the plant and the bending of the shoots) and the wave parameters (wave height, period and direction) so the quantification of wave energy dissipation over seagrasses is difficult to expressed in a universal way.

Various studies on wave attenuation due to coastal vegetation have been performed. In early theoretical and numerical studies the approximation of plants (particularly flexible ones) as rigid cylinders with different values to the drag coefficient is done (Dalrymple *et al* 1984, Kobayashi *et al* 1993). Mendez and Losada (2004) developed an empirical model which includes wave damping and wave breaking over vegetation fields on variable depths. Suzuki and Dijsktra (2007) used a VOF model to simulate wave attenuation over strongly varying beds and vegetation fields, where among others they show that the complex relationship between storm waves and seagrass-induced wave attenuation still needs to be verified. Recently Li and Zhang (2010) developed a 3D RANS model to investigate the hydrodynamics and mixing induced by random waves on vegetation, which is represented as an array of cylinders with the drag coefficient expressed with empirical relation.

Ward et al. (1984) performed field measurements in a shallow estuarine embayment colonized by seagrass communities and showed that wave energy was attenuated by the vegetation, suppressing resuspension and enhancing deposition. In Fonseca and Cahalan (1992) a flume study was performed to measure wave reduction by the use of four species of seagrass. The wave attenuation was found 20- 76 % over 1 m length when the plants were occupying the entire water depth. Bouma et al. (2005) quantified the effect of stiffness of the plant since in their experimental study of the interaction of regular waves with seagrasses and artificial vegetation showed that dissipation was roughly three times higher in the case of vegetation with stiff leaves compared to that with flexible leaves. Recently in Stratigaki *et al (*2010) the results for regular waves passing *P. Oceanica* meadows show that damping of wave height depends on seagrass density and appears to be greater than 35% for a seagrass meadow having density 360 stems/m^2 and occupying half the water column.

A series of experiments with regular and irregular waves were performed in the CIEM (Canal d'Investigació i Experimentació Marítima) wave flume at the Universitat Polytecnica de Catalunya, Barcelona with the objective of measuring wave energy dissipation and transmission over a full scale, artificial *P. Oceanica* patch in intermediate and shallow waters. The effects of submergence ratio h_s/D (h_s=height of seagrass, D=water depth), seagrass density (stems/m^2) on the wave height reduction were investigated for monochromatic waves and they have been described in Stratigaki *et al* (2010).

In this study the main results from full scale experiments on spectral wave and wave flow transformations induced by the full scale artificial *P. Oceanica* patch are presented. Spectral analysis was performed for estimating wave height attenuation and wave induced velocities and determining the effects of plant density, submergence ratio on wave characteristics along the meadow. Measurements of wave height at different locations along the meadow indicate the wave attenuation along the patch for irregular waves, different submergence ratios h_s/D and seagrass densities. Following the analysis of Lowe *et al* (2007) and Manca *et al* (2010) that showed the spectral wave energy dissipation within submerged canopies is frequency-dependent, an attenuation parameter of wave induced velocities is calculated for the frequency components of the incident wave spectrum.

2. EXPERIMENTAL SET UP AND SPECTRAL ANALYSIS

The CIEM wave flume is 100m long, 5m deep and 3 m wide. A sandy slope beach of 1:15 was installed at the end of the flume for the elimination of wave reflection. A 20 m long horizontal and flat sandy area was created in the central part of the flume and the patch of artificial *Posidonia Oceanica*, with a total length L=10.70 m and height h_s=0.55m, was placed above, as shown in Figure 1. The seagrass mimics were made of polypropylene strips and carefully designed to reproduce the flexibility and buoyancy properties typical of the natural *P. oceanica* plants. Figure 2 shows the dimensions and structure of the mimics, while full details on the mimics and on the experiment setup can be found in Stratigraki *et al* (2010).

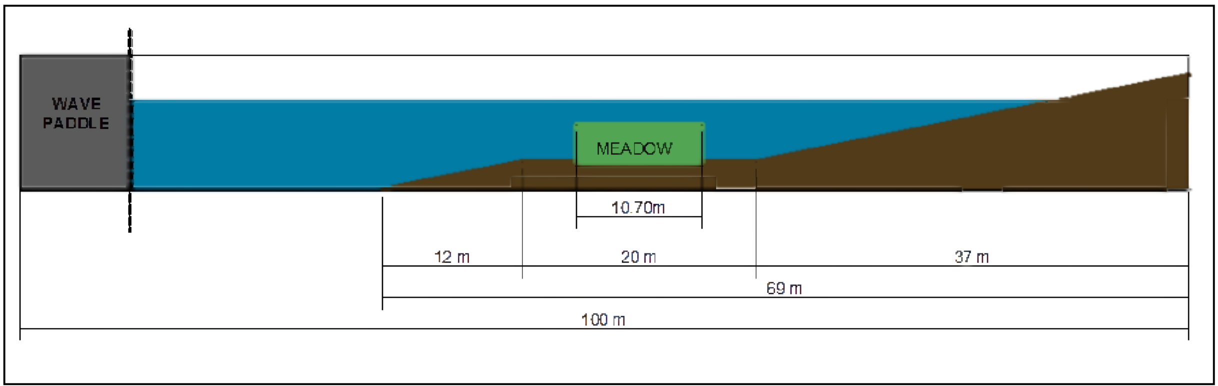

Figure 1 Sketch of the experimental setup of the CIEM flume.

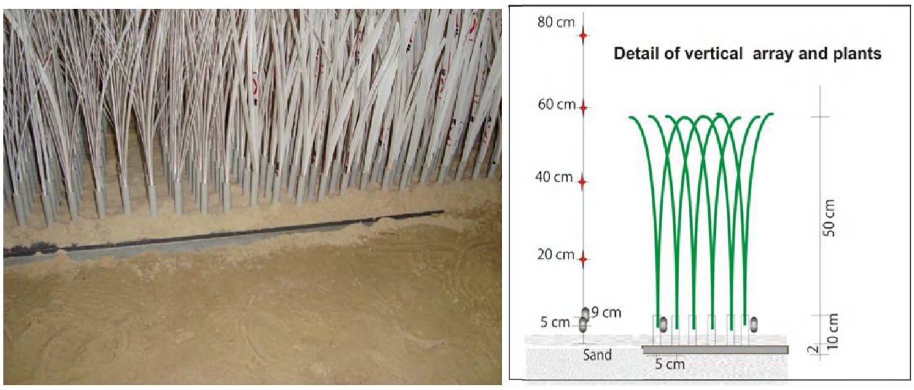

Figure 2 Detail and schematic detail of the artificial plants.

The tests were performed for irregular intermediate water waves (kD =0.76-0.92, Jonswap spectrum with a peak enhancement factor of 3.3) for three different submergence ratios h_s/D (0.37, 0.42 and 0.50) and two different plant densities (360 and 180 stems/m^2) as shown in Table 1. The densities chosen are representatives of shallow sparse *P. Oceanica* patches found in nature. Wave transformation was monitored by wave gauges distributed along the flume. Flow velocities were measured at 3 locations (0.70m in front of the meadow, 1.80m and 8.00m within the meadow, or made dimensionless with the meadow length L, at x/L=-0.07, 0.17 and 0.80 respectively) at 4 different elevations from the flume bed (at z=0.20m, 0.40m, 0.60m and 0.80m or made dimensionless with seagrasses height h_s, at z/h_s=0.36,0.72,1.09 and 1.45 respectively). The location of the wave gauges and current meters along the meadow is shown in Figure 3.

Table 1 Wave and plant characteristics

Water depth at meadow D (m)	Seagrasses height h_s (m)	Wave height H_s (m)	Peak period T_p (s)	kD	Plant density (stems/m^2)	Submergence ratio h_s/D
1.50	0.55	0.40	3.0	0.92	360	0.37
1.30	0.55	0.40	3.0	0.84	360	0.42
1.10	0.55	0.40	3.0	0.76	360	0.50
1.50	0.55	0.40	3.0	0.92	180	0.37
1.30	0.55	0.40	3.0	0.84	180	0.42
1.10	0.55	0.40	3.0	0.76	180	0.50

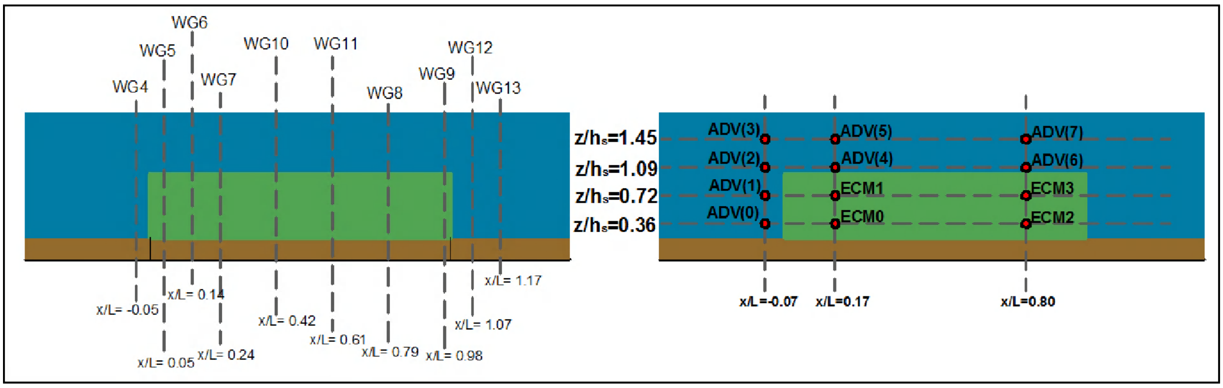

Figure 3 Location of resistive wave gauges and current-meters across meadow.

The velocity time series ($U_{inst}(t)$) were quality checked and the mean value U_m was removed. The de-meaned measured horizontal velocity time series actually represents the wave induced velocity U_w since the random turbulent fluctuations U_t are negligible (as seen in Lowe *et al* 2007).

$$U(t) = U_{inst}(t) - U_m = U_w(t) + U_t(t) \cong U_w(t) \quad (1)$$

The wave induced velocity spectral densities were calculated for all tests and x/L locations along the patch. An attenuation parameter (α_j) was calculated to evaluate the changes in wave-induced spectral flows caused by the canopy and to compare them under different test conditions. It was calculated for the lower canopy at each frequency component of the spectrum following a method similar to that developed for coral reefs (Lowe *et al* 2007):

$$a_j = \left(\phi_j^2 \frac{S_{U,low}}{S_{U,high}^{IN}} \right)^{0.5} = \left(\phi_j^2 \frac{S_{U,z=20cm}}{S_{U\ z=80cm}^{IN}} \right)^{0.5} \qquad (2)$$

With $S_{U,low}$ the wave-induced velocity spectra obtained from the lower ADV (z_{low}=0.20 m) at each of the three x/L locations and $S_U^{IN}{}_{,high}$ the wave induced flow spectra obtained from the higher ADV (z_{high}=0.80 m) at the location upstream the meadow, at x/L=-0.07. The term φ_j is a correction factor to take into account the predicted vertical increase of flow magnitude with distance from the flume bed. It is derived from linear wave theory (Dean and Dalrymple, 1991) and calculated:

$$\phi_j = \frac{\cosh(k_j z_{high})}{\cosh(k_j z_{low})} \qquad (3)$$

Where z_{high} and z_{low} are the elevations of the highest current-meter (z_h=0.80 m) and lowest current-meter (z_l=0.20 m). K_j is the wave number evaluated for each component of the spectrum. For each test the attenuation parameter was calculated at the three x/L locations (x/L=-0.07, 0.17 and 0.80) and for spectral components containing most of the wave energy (95%, between dashed lines shown in Figure 4).

3. ANALYSIS OF RESULTS

The effect of the seagrasses on the wave propagation over the meadow and the resultant energy dissipation can be seen in Figure 4, where the wave energy spectrum measured in the wave gauges is depicted for the meadow with submergence ratio h_s/D= 0.42 and density 360 stems/m^2. There is a gradual decrease of the wave energy along the meadow due to the friction inserted in the flow by the seagrass meadow. Wave energy dissipation is obvious for all components of the wave spectra, especially at peak frequencies. The effect of the plant density on the wave height reduction (H/H_{in}) can be seen in Figure 5, for all three submergence ratio configurations. For both densities the incident wave height (H_{in} as measured in x/L=-0.05) is reduced by ~20-30%, with larger attenuation observed for the more dense meadow. It can also be noticed that due to the “plant resistance” to the flow, in the upward side of the meadow, part of the wave energy is reflected and the wave height increases (x/L=0.05) for the more dense case (360 stems/m^2). The effect of submergence ratio on wave attenuation is also evident as seen in Figure 6, for both plant densities.

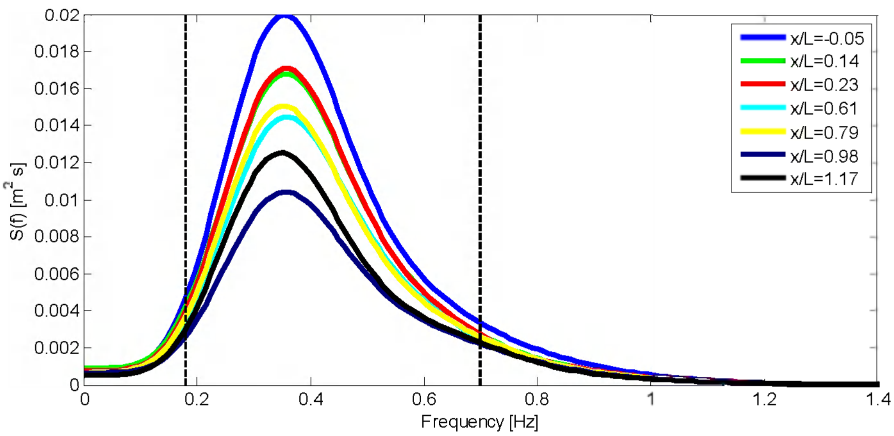

Figure 4 Wave spectrum transformation along the meadow.
(H_s= 0.40 m T_p= 3.0 s, h_s/D= 0.42 and density 360 stems/m^2)

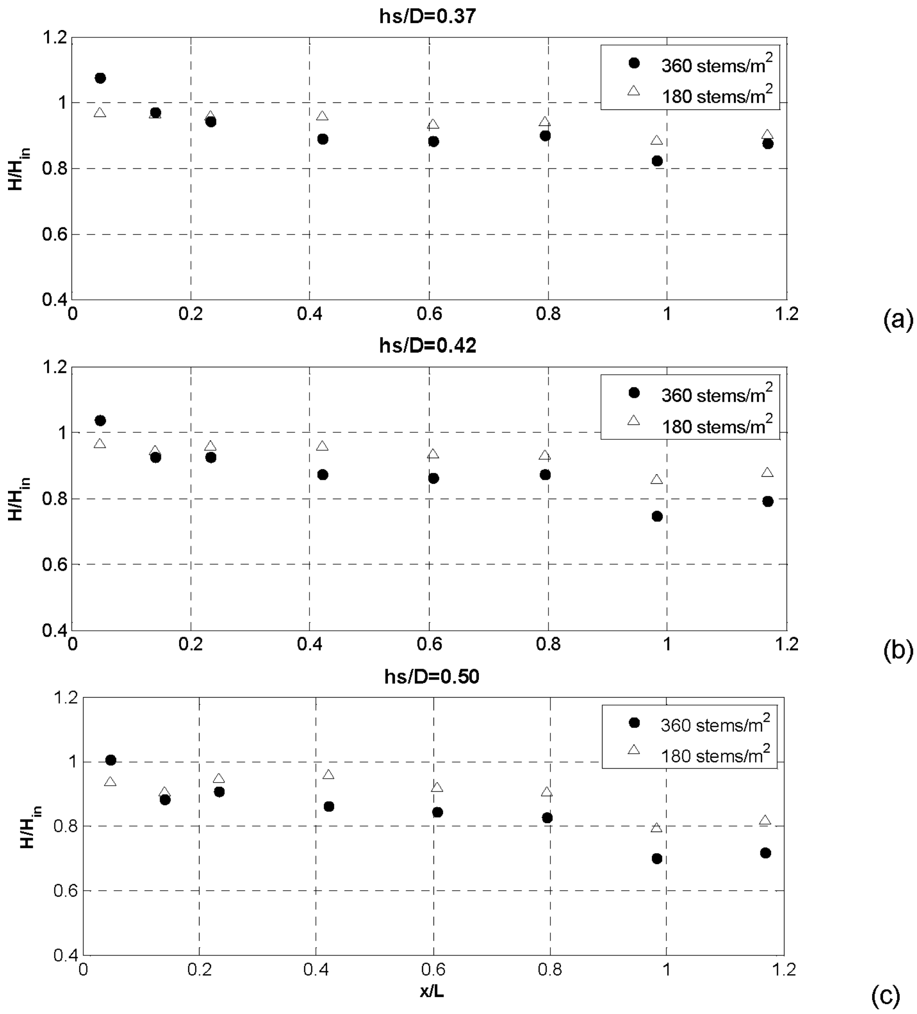

Figure 5 Effect of plant density on wave height decay along the meadow. Submergence ratio: (a) h_s/D= 0.37 (b) h_s/D= 0.42 and (c) h_s/D= 0.50

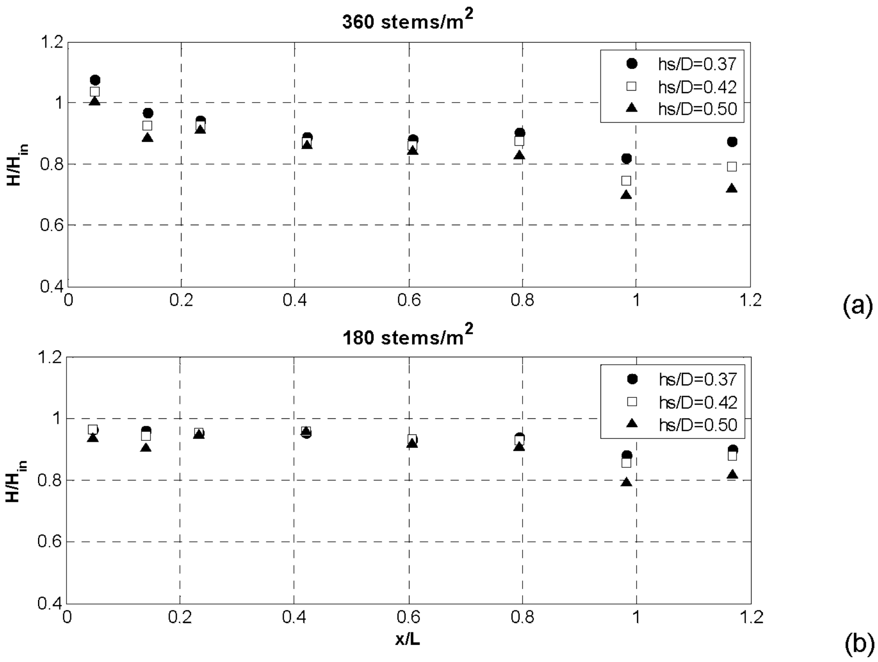

Figure 6 Effect of submergence ratio on wave height decay along the meadow. Plant density: (a) 360 stems/m^2 (b) 180 stems/m^2

The spectrum of the of wave induced velocities measured in the lower canopy (z/h_s=0.36) at the three locations along the flume is shown in Figure 7, for submergence ratio h_s/D= 0.42 and density 360 stems/m^2, together with the attenuation parameter. It can be seen that the velocities of the longer wave components (T_j>T_p=3 s) are mostly attenuated, while the short wave (smaller period) components in the upward side of the meadow have values a_j>1. This shows the complicated flow field inside the meadow, the attenuation of velocities from the vegetation field and partly energy transfer from the longer period to the smaller period wave components. This is more evident from Figure 8 and 9 where the attenuation parameter is depicted as calculated for all the cases at the three location along the patch (x/L=-0.07, 0.17 and 0.80). The small values of a_j at the leeward side of the meadow (x/L=0.80) indicate the efficient velocity reduction, based on the velocities measured in the lower canopy (z/h_s=0.36). However if the velocities measured at the higher ADVs, at z=40cm (z/h_s=0.72) and z=60cm (z/h_s=1.09), are used for the calculation of a_j, the results do not show a specific trend for the a_j, showing the complicated velocity structure near the edge of the meadow, especially over the edge, for z/h_s=1.09.

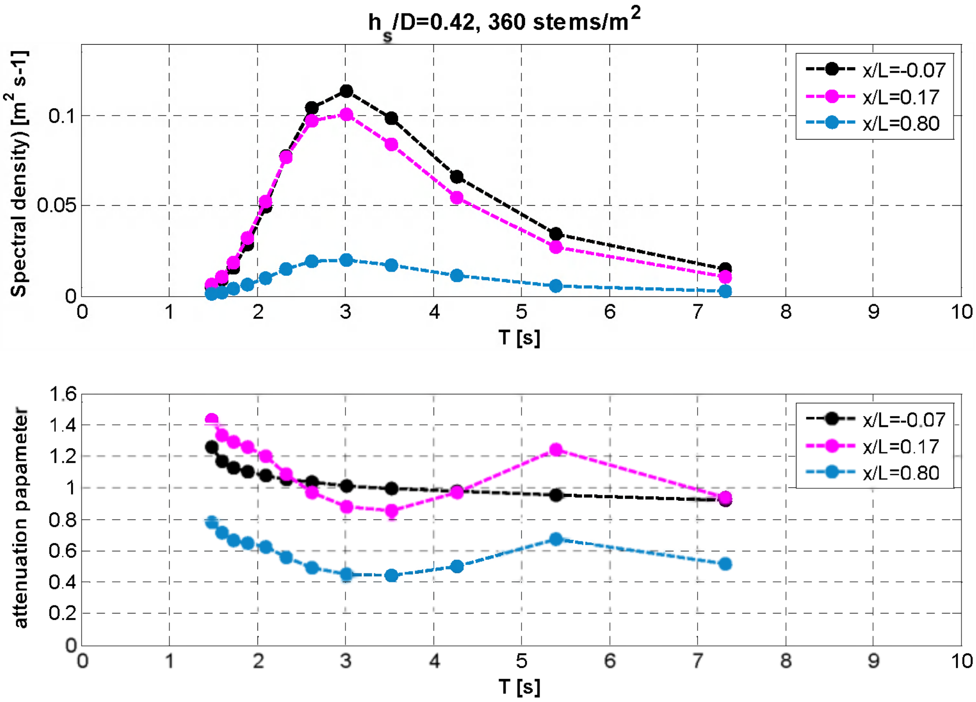

Figure 7 (a) Spectra of wave induced velocities measured in the lower canopy (z/h_s=0.36) at the three locations along the flume (b) Attenuation parameter for the spectral components (T_j).

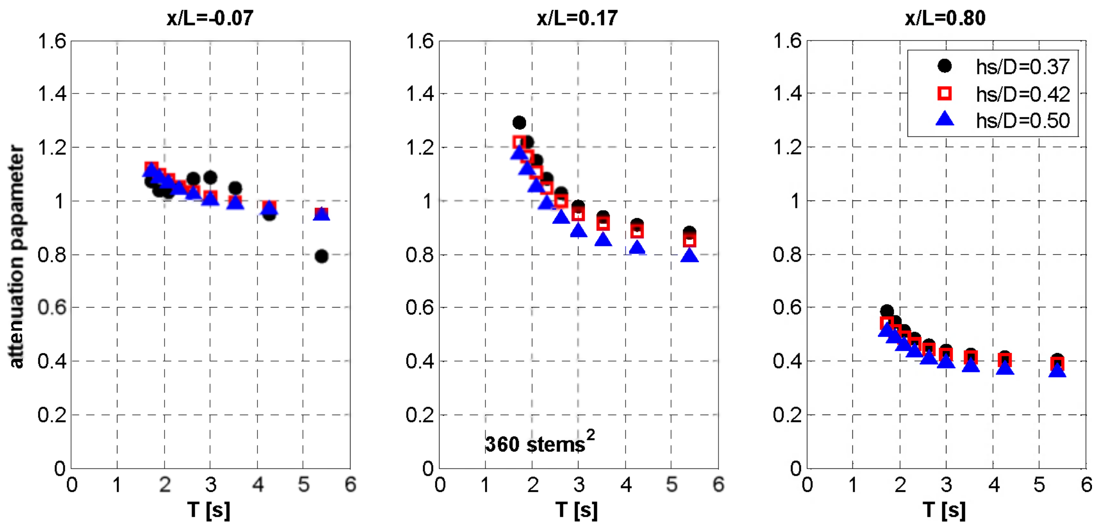

Figure 8 Effect of h_s/D on the attenuation coefficient (α_j) calculated for each wave period (T_j) of the wave-induced velocity spectra component- Plant density: 360 stems/m^2.

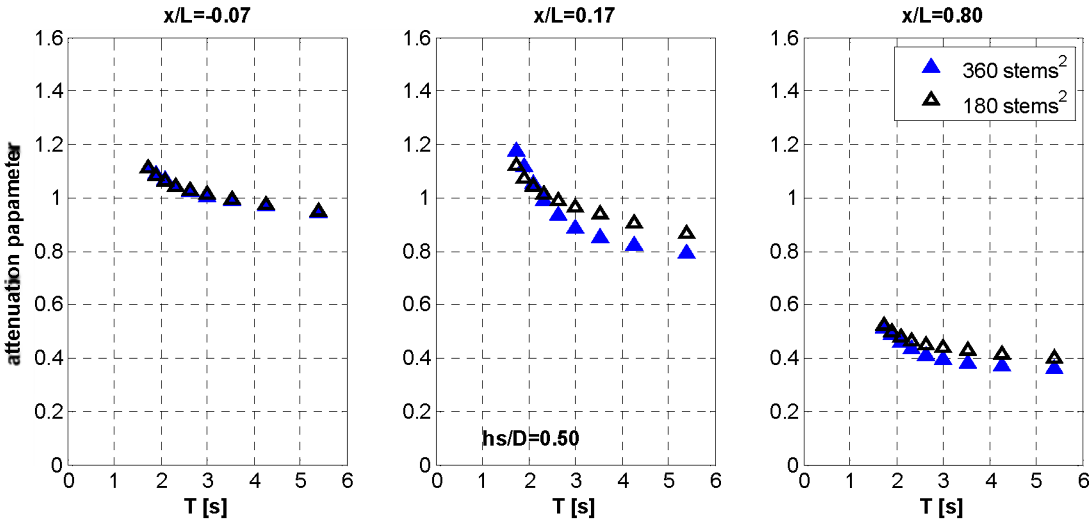

Figure 9 Effect of plant density on the attenuation coefficient (α_j) calculated for each wave period (T_j) of the wave-induced velocity spectra component- Submergence ratio: h_s/D= 0.50.

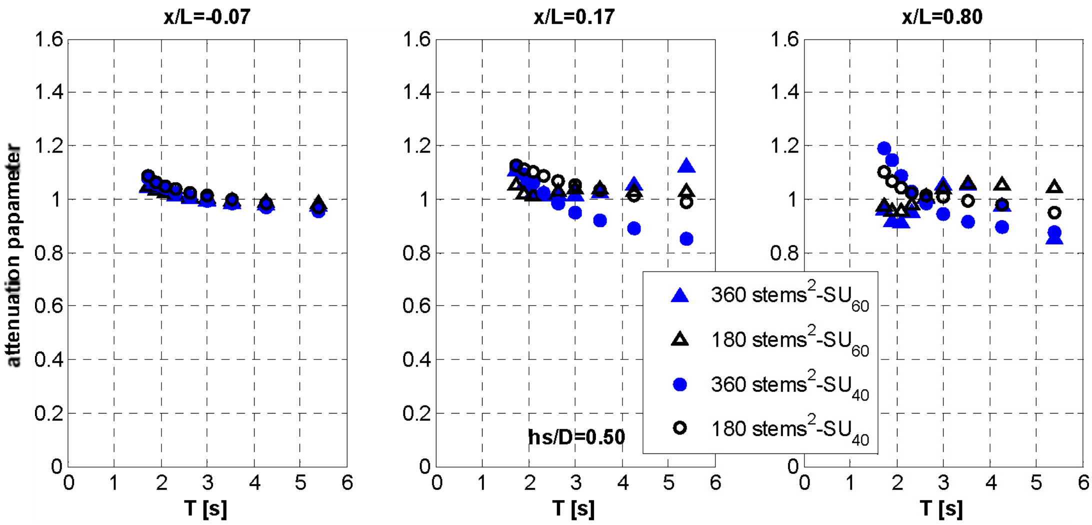

Figure 10 Attenuation coefficient (α_j) for the cases as Figure 9, as calculated for the ADVs at z=40cm and z=60cm ($SU_{,low}$= $SU_{,40}$ and $SU_{,low}$= $SU_{,60}$ respectively).

4. CONCLUSIONS

The wave propagation over a seagrass bed, the resultant attenuation of the wave height and the wave-induced velocities has been studied experimentally, for irregular intermediate water waves. Results show the efficient wave height attenuation, ranging from 15%-30%, depending on the seagrass characteristics, the submergence ratio and plant density. Wave energy dissipation is obvious for all components of the wave spectra, especially at peak frequencies. Wave attenuation increases with increasing plant density and submergence ratio.

With regard to the velocity structure, it is shown that the velocities of the longer wave components (T_j>T_p=3 s) are mostly attenuated compared to the short wave components. This shows the complicated flow field inside the meadow, the attenuation of velocities from the vegetation field and partly energy transfer from the longer period to the smaller period wave components. The results from the velocities measured at the edge of the seagrass meadow do not show a specific trend for wave-induced velocities attenuation, showing the complicated velocity structure near the edge of the meadow, due to the nonlinear interaction of the wave motion and the movement of the leaves of the seagrasses.

5. ACKNOWLEDGMENTS

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