Coastal Engineering 73 (2013) 71–83

Contents lists available at SciVerse ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Wave damping over artificial *Posidonia oceanica* meadow: A large-scale experimental study

Theoharris Koftis [a],*, Panayotis Prinos [a], Vasiliki Stratigaki [b]

[a] Hydraulics Laboratory, Department of Civil Engineering, Aristotle University of Thessaloniki, Thessaloniki, 54124, Greece
[b] Department of Civil Engineering, Ghent University, Technologiepark 904, Zwijnaarde, B-9052, Belgium

ARTICLE INFO

Article history:
Received 15 September 2011
Received in revised form 18 October 2012
Accepted 24 October 2012
Available online 16 November 2012

Keywords:
Posidonia oceanica
Wave damping
Drag coefficient
Velocity attenuation
Artificial sea grass
Large scale experiment

ABSTRACT

An experimental study, conducted in the large wave flume of CIEM in Barcelona, is presented to evaluate the effects of *Posidonia oceanica* meadows on the wave height damping and on the wave induced velocities. The experiments were performed for irregular waves from intermediate to shallow waters with the dispersion parameter h/λ ranging from 0.09 to 0.29. Various configurations of the artificial *P. oceanica* meadow were tested for two stem density patterns (360 and 180 stems/m^2) and for plant's height ranging from 1/3 to 1/2 of the water depth.

The results for wave height attenuation are in good agreement with the analytical expressions found in literature, based on the assumption that the energy loss over the vegetated field is due to the drag forces. Based on this hypothesis, an empirical relationship for the drag coefficient related to the Reynolds number, Re, is proposed. The Reynolds number, calculated using the artificial *P. oceanica* leaf width as the length scale and the maximum orbital velocity over the meadow edge as the characteristic velocity scale, ranges from 1000 to 3500 and the drag coefficient C_d ranges from 0.75 to 2.0.

The calculated wave heights, using the analytical expression from literature and the proposed relationship for the estimation of C_d, are in satisfactory agreement with those measured. Wave orbital velocities are shown to be significantly attenuated inside the meadow and just above the flume bed as indicated by the calculation of an attenuation parameter. Near the meadow edge, energy transfer is found in spectral wave velocities from the longer to the shorter wave period components. From the analysis it is shown that the submerged vegetation attenuates mostly longer waves.

1. Introduction

Sustainable protection of coastal areas with respect to the marine ecosystem is of high importance and bioengineering can be a novel tool for such service. Bioengineering is the use of living materials such as plants or reef builders to alleviate the need of hard construction measures (de Oude et al., 2010). This need for mitigation of wave action and/or flooding and coastal erosion hazards with low environmental impact on the coastal environment can be satisfied with the use of natural coastal defense "structures" such as seagrass meadows.

Seagrasses are marine plants that have roots, stems and leaves. From approximately 50 species worldwide (den Hartog, 1977) *Posidonia oceanica* is the most common seagrass species in the Mediterranean Sea and is usually distributed from shallow subtidal waters to a depth of 50 m in clear conditions (Borum et al., 2004). *P. oceanica* can colonize soft substrates such as sand in wave-sheltered areas and also attach to rocks being exposed to relatively high wave energy and wind driven currents (Koch et al., 2006). The importance of seagrasses regarding biological and physical aspects has been well recognized; due to their capacity to alter their environment, seagrasses have been referred to as "ecosystem engineers". Seagrass meadows are of great importance for maintaining biodiversity since they are highly productive and can serve as important nursery grounds for numerous species of algae, fish and invertebrates both above and below the seabed (Green and Short, 2003). Regarding the coastal protection aspect, a service commonly listed for seagrasses is sediment and shoreline stabilization, achieved by slowing down water motion and current flow and by reducing sediment suspension (Borum et al., 2004; Fonseca and Cahalan, 1992). In the Tigny et al. (2007) field study, the same effects are found; *P. oceanica* meadows significantly affect the littoral geomorphology, providing biogenic sediments, controlling beach slope, and acting as a "brake" on coastal water masses.

With regard to the wave and seagrass interaction, 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

---

* Corresponding author. Tel.: +30 2310 995877; fax: +30 2310 995672.
E-mail address: thkoftis@civil.auth.gr (T. Koftis).

0378-3839/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.coastaleng.2012.10.007

(Koch et al., 2006). The degree of wave attenuation depends both on the seagrasses' characteristics (the plant's density, the seagrass 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 express in a universal way (Mendez and Losada, 2004).

Various laboratory and field studies on wave attenuation due to seagrasses have been performed, with large variability of the results for wave damping over seagrass meadows that confirm the complexity of such flow system. Wave height reduction over vegetated seabed was studied by Fonseca and Cahalan (1992). Four common North American seagrass species; *Halodule wrihtii*, *Syringondium filiforme*, *Thalassia testudinum* and *Zostera marina* were harvested from several sites along the Florida Keys and were placed in a 6 m long wave flume. Wave height attenuation was found between 20% and 76% (~40% on average) over 1 m length when the plants were occupying the entire water depth. Artificial plants were used in the experiments of Ota et al. (2004) in a 30 m long wave flume. Each stem was formed by four leaves made of polyester and all stems constituted a 6 m long vegetated seabed with stem density of 1000 stems/m^2, occupying half the water depth. The experimental results were compared with a simple numerical model based on the linear wave theory and satisfactory agreement was found for values of the drag coefficient $C_d = 1.3$. Bradley and Houser (2009) performed a field study in a microtidal bay in northwest Florida, where the main species of the meadows were *T. testudinum* and *H. wrightii*. The study was performed for small Reynolds numbers ($200 < Re < 800$) and for these conditions they obtained large values for the drag coefficient ($1.5 < C_d < 100$) and suggested a relationship for the drag coefficient with either the Reynolds or the Keulegan–Carpenter number. The measured wave height decay for submerged vegetation was found to be described well with an exponential function proposed by Kobayashi et al. (1993) and Mendez et al. (1999). The efficient scaling and reproduction of the physical plant's flexibility by artificial meadows have been important features in most recent studies. In Elginoz et al.'s (2011) experimental study, the leaves of the artificial models were made of Nickel-chrome stripe wire with a density of $\rho = 7757$ kg/m^3 and a modulus of elasticity $E = 1.98$ GPa. The model was in a 1:10 scale compared with prototype conditions and this analogy was selected to reproduce both the wave conditions and the plant's characteristics. The model reproduced a natural meadow with 87 stems/m^2, the leaf length varied from 0.10 to 0.50 of the water depth approximately and was placed on a 1:5 slope beach at the end of the 24 m long wave flume. The results showed that the ratio of the wave height on the vegetated side to the unvegetated side is between 0.78 and 0.94. In Sánchez-González et al. (2011) the experiments were conducted also in a 1:10 geometric scale in a 46.3 m long wave flume. The artificial plant leaves were made of polyethylene and polypropylene with a density of $\rho = 900 \pm 20$ kg/m^3 and a modulus of elasticity $E = 1.6$ GPa. The results regarding wave damping were found to follow the exponential decay law and steeper waves were found to be mostly attenuated. The experiments were performed in a range of $100 < Re < 1500$ and the obtained values for the drag coefficient C_d were in the range $0.1 < C_d < 1.0$ approximately. They showed that the dependence of C_d on the Keulegan–Carpenter number, ranging from 10 to 250 approximately, is stronger than that on the Reynolds number.

The attenuation of wave induced velocities has been studied experimentally to address the ability of the plants to slow the water motion, increase sedimentation and provide efficient protection of the beaches against erosion. The interaction of flow and seagrass canopies of *Amphibolis antarctica* species, which differ morphologically from more commonly studied blade-like seagrasses such as *Zostera* and *Thalassia*, was performed in the field study of Verduin and Backhaus (2000). A series of velocity measurements were obtained within, above and adjacent to *A. antarctica* meadows for swell wave conditions of the study area ($T = 13$–16.5 s). The results showed an overall damping effect since the power spectra of the velocity data revealed a specific reduction in energy within the canopy. Granata et al. (2001) measured the particle and flow distribution within seagrass meadows in a Northeast coast of Spain for both low and high wave and current activities. The results revealed the 3-dimensionality of the meadow, showing that it acts as a bluff body diverting flow over the meadow, while producing a secondary circulation cell at the meadow's edge. Lowe et al. (2007) performed experiments with rigid cylinders representing a submerged canopy for the quantification of the wave induced velocities by the introduction of an attenuation parameter. The results showed that longer-period components in the wave spectrum are significantly more attenuated than shorter-period components. Enhancing these experimental results Lowe et al. (2008) presented a mathematical model based on porous flow to account for the wave-driven flow within the canopy. The model unknown parameters such as the friction coefficient, C_f, dimensional drag parameter, β, and inertial coefficient, C_M, were calibrated by the experimental data. Experiments with a flexible artificial canopy, made of polyethylene, with $\rho = 920$ kg/m^3 and modulus of elasticity $E = 0.3$ GPa were carried out in a 20 m long wave flume in Luhar et al. (2010). The experiments were performed for a range of parameters, stem density 300–1800 stems/m^2 and plant leaves height ranging from 1/2 to 1/1 of the water depth. The results showed that a local circulation pattern is revealed within the meadow.

Numerical modeling for such wave–seagrass interaction is a demanding task, since the parameters of the plant stiffness and movement with wave motion are difficult to model. Therefore in early theoretical and numerical studies, plants have been simulated as rigid cylinders with different values to the drag coefficient (Dalrymple et al., 1984; Kobayashi et al., 1993). Mendez and Losada (2004) developed an empirical model for wave transformation on vegetation fields that included wave damping and wave breaking over vegetation fields on variable depths. Based on a nonlinear formulation of the drag force, the model was calibrated for a specific type of plant (*Laminaria hyperborea* kelp) and the results were compared with available experimental data. Chen et al. (2007) developed a model to account for the interactions between waves, currents and sediment transport in seagrass systems within the nearshore circulation model SHORECIRC and the REF/DIF wave model. The drag coefficient C_d accounting for currents and waves was estimated based on an average drag coefficient $C_d \sim 1.17$ and accounting for the seagrass density and submergence. Li and Yan (2007) developed a three-dimensional numerical model to simulate the wave–current–vegetation interaction using the RANS equations where the extra drag force term due to vegetation takes different values depending on the nature of the flow; unidirectional flow through vegetation, wave–vegetation interaction and wave–current–vegetation interaction. The drag coefficient C_d for the wave–vegetation case was calculated using the Mendez et al., 1999 empirical expression related to the Reynolds number. Suzuki and Dijkstra (2007) used a Volume of Fluid model to simulate wave attenuation over strongly varying beds and vegetation fields, both stiff and submerged flexible artificial vegetation on a sloped bed and a flat bed. In Li and Zhang (2010) a 3D RANS model was employed for the study of the hydrodynamics and mixing induced by random waves on vegetation. The vegetation was represented as an array of cylinders with the drag coefficient expressed with the empirical expression proposed by Mendez and Losada (2004), while the results of the model were in good agreement with experimental data. Recently Huang et al. (2011) presented a numerical model based on the Boussinesq equations, for the study of the interaction of solitary waves with emergent rigid vegetation. The model used values for the drag coefficient calculated from the experimental part of the study, which were in the range of $1.41 < C_d < 2.45$.

From the above mentioned studies the following main issues regarding the wave and submerged vegetation interaction arise: (i) the degree of wave height damping (ii) the efficient numerical modeling of such flows that strongly depend on the estimation of the meadow drag coefficient and (iii) the attenuation of wave-induced velocities. The