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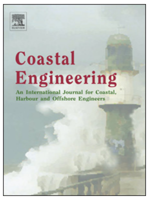

A new formulation for vegetation-induced damping under combined waves and currents

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ABSTRACT

Based on energy conservation a new analytical formulation for the evaluation of wave damping under the combined effect of waves and both following and opposing currents is presented. The formulation obtained for regular and random waves allows the derivation of analytical expressions for the vegetation drag coefficient as a function of wave damping parameters. These parameters are calibrated using a unique experimental set obtained in a large-scale wave basin considering the interaction of waves and currents with real vegetation representative of salt marshes, namely *Spartina anglica* and *Puccinellia* maritime. Comparisons show the quality of the analytical formulation under different hydrodynamic conditions, vegetation species and various Reynolds numbers formulated in terms of plant characteristics such as the deflected plant length accounting for the flow-induced bending of the vegetation. The new formulation can be useful to be implemented in phase averaged and phase resolving numerical models of wave propagation.

1. Introduction

Coastal vegetation, such as salt marshes or seagrasses, serves as buffer areas against flooding and erosion (e.g.: McGranahan et al., 2007; FitzGerald et al., 2008; Duarte et al., 2013). These habitats develop in areas commonly affected by tidal currents or wave-induced currents flowing simultaneously with wind or swell waves (e.g.: Ysebaert et al., 2011). Therefore, they are subjects to the combined effect of both waves and currents. To date, the vast majority of studies focusing on energy dissipation induced by coastal vegetation have studied current flows (e.g.: Fonseca and Cahalan, 1992; Ghisalberti and Nepf, 2002; Bouma et al., 2013) or wave conditions (e.g.: Kobayashi et al., 1993; Mendez et al., 1999; Maza et al., 2013) separately.

The effects of a following (propagating in the same direction) or opposing uniform current on the propagation of surface gravity waves have been studied by several authors. Longuet-Higgins and Stewart (1960, 1961) first introduced the wave and current interaction in the energy flux equation by means of the radiation stress. A first-order velocity potential for an irrotational wave–current field over a horizontal bottom was proposed by Peregrine (1976) and then adopted by several authors such us Baddour and Song (1990). They developed fourth-order equations for the determination of wavelength and height, and the energy flux density is expressed to the second order in wave amplitude. Later, Jonsson and Arneborg (1995) extended these equations to higher-order Stokes waves. Many analytical expressions can be found in the literature to describe the wave–current interaction, but the complexity of this nonlinear interaction has lead to the use of numerical tools to overcome complex configurations and higher-order effects. Recently, numerical models have been developed to accomplish the highly nonlinear effects present in the wave–current interaction. Approaches based on the mild-slope wave equation (Chen et al., 2005) or Boussinesq equations (Zou et al., 2013) have been used to model the nearshore wave–current interaction. More sophisticated models based on RANS equations (Zhang et al., 2014) have been presented in recent years.

Besides the aforementioned wave and current interaction studies, the momentum damping produced by aquatic vegetation under wave and current conditions has been poorly characterized. Based on the conservation of energy equation, Dalrymple et al. (1984) was the first to formulate a semiempirical expression to consider the energy loss for regular waves propagating through vegetation. The Dalrymple et al. (1984) formulation was later extended by Mendez and Losada (2004) for random waves. Otta et al. (2004) extended the wave decay model presented by Kobayashi et al. (1993) for wave and current conditions considering a linear combination of the waves and currents. Later, Li and Yan (2007) presented a three-dimensional model based on RANS equations, in which advection, diffusion and pressure terms are solved separately and vegetation is modeled as a sink of momentum. They concluded that current flowing in the same direction as wave propagation increases wave decay based on computed vertical velocity profiles. These results contradict the laboratory measurements presented by Paul et al. (2012) which conducted flume experiments using vegetation flexible mimics to study the effect of waves combined with a following current. They found that currents reduce wave energy dissipation. Recently, Hu et al. (2014) proposed a new empirical relationship between

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the drag coefficient and a new Reynolds number based on laboratory data. This formulation was obtained for a non-predictable Reynolds number based on a mean velocity measured inside the canopy field. Tests were performed using rigid cylinders and currents in the same direction as wave propagation. The analysis of different current velocity values reveals different effects on wave damping. Small current velocities lead to less wave damping in comparison to pure wave conditions and the opposite, more dissipation, occurs for higher currents. However, tests for different current velocities were carried out changing the generated incident wave height and, therefore results obtained are not directly comparable. Furthermore, the proposed analytical model for current–wave flows presents some limitations since it is obtained for shallow water conditions considering the linear superposition of wave and current velocities without considering the interaction between them.

Following the energy flux conservation approach presented by previous authors (e.g.: Dalrymple et al., 1984; Mendez and Losada, 2004), this work aims to obtain the relationship between the energy loss produced due to the mechanical work carried out on the vegetation and the induced wave damping when waves and currents are acting in the same and in opposite direction considering the interaction between both flow conditions. The analytical model proposed here is based on the experimental results of experiments conducted in the Cantabria Coastal and Ocean Basin (CCOB) large basin at prototype scale and using two real vegetation species. The experimental set-up is presented in Section 2. The new model for the wave damping under wave–current-vegetation interaction is presented in Section 3. In Section 4, the new formulation is used to fit experimental data and found new expressions for the drag coefficient under pure waves and wave and current conditions. Finally, some conclusions are presented in Section 5.

2. Experimental set-up

Experiments were conducted in the CCOB large-scale facility under waves combined with following and opposing currents. Two salt marsh species were grown up from seeds to test real vegetation under different flow conditions. The flow and vegetation characteristics are specified in the following sections. A more detailed description of the experimental setup can be found in Lara et al. (submitted for publication) and Maza et al. (submitted for publication).

2.1 . Flow conditions

The energy dissipation induced by real vegetation is studied for different flow conditions. Five different regular and one random wave trains (Table 1) are tested under three different flow conditions (pure waves, waves and current in the same direction and waves and current in the opposite direction). Wave conditions were selected based on field conditions under average storm events. Two different water depths are considered: 0.40 and 0.60 m.

The six wave conditions were tested considering wave trains including 200 waves, allowing a statistical representative number of waves. For regular waves, more than 150 waves are recorded with uniform characteristics at the generation boundary composed of 64 independent wave makers. All cases in Table 1 were tested in combination with a 0.30 m/s current acting in both directions. Current velocities were chosen based on Bouma et al. (2005). Measurements began for 200 waves after a uniform current profile was reached. Consequently, a total of 18 different flow conditions were tested.

Table 1
Wave conditions for regular and irregular waves.

Wave conditions	Type	H(m) or Hs(m)	T(s) or Tp(s)
R1	Regular	0.15	2
R2	Regular	0.20	2
R3	Regular	0.20	1.2
R4	Regular	0.20	1.7
R5	Regular	0.20	2.2
I	Irregular	0.12	1.7

2.2 . Vegetation characteristics

Tests were conducted to analyze flow interaction with two real salt marsh vegetation species, namely, *Spartina anglica* and *Puccinellia maritima*. These two species develop in the pioneer zone and the lower marsh of the marsh zone, respectively. They were selected to provide information on sensitivity to different biomechanical properties, namely differences in flexibility of both species as well as geometry and biomass. The Young's modulus, geometric dimensions and dry weight were measured for both species and are summarized in Table 2.

Energy dissipation induced by the drag force acting on the vegetation is dependent on the plant length. Bending observed for flexible vegetation results in a reduced drag-forming area of the canopy. Consequently, the actual vegetation length affected by the flow depends on the plant behavior under different flow conditions (waves and currents) and will be a function of plant geometry, flexibility and buoyancy (Luhar and Nepf, 2011). Plant motion influences the energy dissipation induced by plants.

The two species considered in this study behave differently under identical flow conditions due to their different biophysical properties. *S. anglica* responds to flow like a cantilever whereas *P. maritima* exhibits a whip-like motion. For *P. maritima* the effect of current velocity is a strong bending due to its high flexibility. Fig. 1 presents a schematic representation of the motions experienced by both species under pure wave conditions and under combined waves and currents, extracted from visual observations during the experiments.

Based on the above it can be concluded that including the influence of the deflected plant length on the estimation of the dissipation produced by flexible vegetation is very important. As shown in Fig. 1, the deflected plant length is defined as the actual length that is affecting the flow due to plant bending. Not considering the reduced drag-forming area due to bending may lead to an overestimation of energy dissipation. Luhar and Nepf (2011) proposed a new formulation to calculate the nondimensional deflected length of a plant based on its bending angle (θ). An estimation of the bending angle was obtained for different flow conditions by means of video recording during the experiments. The observed mean bending angle for *S. anglica* was almost zero, whereas *P. maritima* bent according to flow velocities, especially when current was acting combined with waves. A mean vertical angle between 30 and 40° was estimated for pure wave conditions. This value was observed to increase strongly when current was acting, yielding values between 45 and 55°. The Luhar and Nepf (2011) formulation presented in Eq. (1) is used to calculate the relationship between the deflected length (l_D) and the plant length (l).

$$\frac{l_D}{l} = \int_0^l \cos\theta dz \tag{1}$$

For *P. maritima* and considering waves only, $\frac{l_D}{l}$ ratio is 80%, whereas under the combined effect of waves and currents this ratio is reduced to 60%. Therefore, the combined effect of waves and currents contributes reducing the drag-forming area.

Another aspect that influences energy dissipation is vegetation density. In this work three different plant densities (numbers of shoots per square meter) were considered for *P. maritima* and two for *S. anglica* in the experimental setup. Densities tested are summarized in Table 3.

High densities, P100 and S100, are representatives of field conditions whereas the lower densities (P66, P33 and S66) are used to carry out a sensitivity analysis of different vegetation conditions on drag imposed by vegetation. Lower densities may be representatives of vegetation seasonality or different health conditions. P100 and S100 were tested