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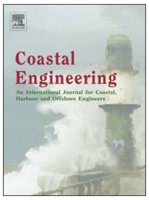

Plant stiffness and biomass as drivers for drag forces under extreme wave loading: A flume study on mimics

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ABSTRACT

Moving water exerts drag forces on vegetation. The susceptibility of vegetation to bending and breakage determines its flow resistance, and chances of survival, under hydrodynamic loading. To evaluate the role of individual vegetation parameters in this water-vegetation interaction, we conducted drag force measurements under a wide range of wave loadings in a large wave flume. Artificial vegetation elements were used to manipulate stiffness, frontal area in still water and material volume as a proxy for biomass. The aim was to compare: (i) identical volume but different still frontal area, (ii) identical stiffness but different still frontal area, and (iii) identical still frontal area but different volume.

Comparison of mimic arrangements showed that stiffness and the dynamic frontal area (i.e., frontal area resulting from bending which depends on stiffness and hydrodynamic forcing) determine drag forces. Only at low orbital-flow velocities did the still frontal area dominate the force-velocity relationship and it is hypothesised that no mimic bending took place under these conditions.

Mimic arrangements with identical stiffness but different overall material volume and still frontal area showed that forces do not increase linearly with increasing material volume and it is proposed that short distances between mimics cause their interaction and result in additional drag forces. A model, based on effective leaf length and characteristic plant width developed for unidirectional flow, performed well for the force time series under both regular and irregular waves. However, its uncertainty increased with increasing interaction of neighbouring mimics.

1. Introduction

It has been widely recognised that the interaction of flexible littoral vegetation (e.g. seagrass, salt marsh) with both oscillatory and unidirectional flow in shallow marine environments leads to a reduction of water velocity and hydrodynamic energy (Lightbody and Nepf, 2006; Möller et al., 1999; Yang et al., 2012). Moreover, recently Möller et al. (2014) showed that a transplanted salt marsh is even capable of substantial wave height reduction under simulated storm surge conditions. Given the increasing need for coastal protection, there is high interest in nature-based coastal defence. Using intertidal vegetation in such schemes is one of the most promising approaches to date (Barbier et al., 2008; Bouma et al., 2014; Temmerman et al., 2013). However, implementing such nature-based coastal defence schemes requires high quality modelling capability of flow and wave dissipation by vegetation fields, and hence a mechanistic understanding of vegetation-hydrodynamic interaction. The flow reducing capacity of vegetation is based on the drag the vegetation exerts on the flow (either unidirectional or oscillatory) which can be expressed by the drag coefficient C_D. In return, the vegetation canopy is exposed to these drag forces and its resistance to these determines its survival (Callaghan et al., 2007; Denny et al., 1998). Estimation of these forces has therefore received considerable attention from both the hydraulic (Chen et al., 2011; Henry and Myrhaug, 2013; Siniscalchi et al., 2012) and ecological (Carrington, 1990; Gaylord et al., 2003; Sand-Jensen, 2003) research communities.

The drag expressed by C_D can be used to estimate the rate of frictional dissipation which leads to the reduction of wave energy (Dalrymple et al., 1984). Several models have been developed to estimate C_D from wave and vegetation parameters (Dalrymple et al., 1984; Kobayashi et al., 1993; Maza et al., 2013; Méndez and Losada, 2004), expressed

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as a function of either the Reynolds number *Re* or the Keulegan-Carpenter number *KC* (see Henry et al. (2015) for a comprehensive review). These models have been applied to wave dissipation datasets from both field (Bradley and Houser, 2009; Paul and Amos, 2011) and laboratory studies (Augustin et al., 2009; Houser et al., 2015; Stratigaki et al., 2011) in low to medium energy wave conditions. Dissipation of waves with heights in excess of 20 cm in water depths > 1 m above a typical salt marsh canopy has so far only been measured by Möller et al. (2014) in a large wave flume, and by Yang et al. (2012) in the field. Möller et al. (2014) show that under high incident wave energy levels the structural integrity of the vegetation elements is exceeded and plant elements begin to fold and break, rather than flex and bend as they do in response to low to medium energy conditions. As vegetation response changes with changing hydrodynamic forcing, a drag coefficient which assumes plant rigidity can thus not necessarily be used to calculate the drag forces acting on the vegetation, particularly when extrapolating to extreme conditions (Bell, 1999). It is thus necessary to determine the drag forces acting on salt marsh vegetation directly, in order to assess its susceptibility to physical damage during storm surges. Only then will it be possible to properly assess vegetation resilience under such conditions.

Available direct measurements of drag forces on natural plants are scarce and, due to the restricted dimensions of most flumes, typically limited to small waves (wave height $H \leq 7$ cm) or low-velocity unidirectional flow (Bouma et al., 2005, 2010). Laboratory measurements with two intertidal plant species (*Spartina anglica* and *Zostera noltii*) showed that under those relatively benign conditions, the drag forces decrease with decreasing stiffness and suggest that bending of the flexible plants causes this reduction (Bouma et al., 2005). This observation agrees well with other research undertaken on drag reduction and reconfiguration (Boller and Carrington, 2006; O'Hare et al., 2007; Siniscalchi and Nikora, 2012), indicating that the effective frontal area after reconfiguration is a major factor in explaining drag. On the other hand, systematic studies with both real (Bouma et al., 2010; Paul and Amos, 2011) and artificial (Paul et al., 2012) flexible coastal vegetation suggests that wave attenuation, and hence C_D, in shallow water environments is governed by the amount of above ground standing biomass rather than by individual parameters such as leaf length or vegetation stiffness. This observation is also supported by a study on fresh water macrophytes (Penning et al., 2009).

According to theory, the drag force *F* acting on a plant, is related to the frontal surface area *A* which in return depends on vegetation stiffness (Aberle and Järvelä, 2013; Bouma et al., 2010). This relationship can be described as

$$F = \frac{1}{2}\rho C_D A u^{\beta} \quad (1)$$

where ρ is density of water, *u* is water velocity and β is a tuning parameter which depends on the streamlining of the plant, typically < 2 for flexible objects, and 2 for rigid objects (Vogel, 1994). Biomass is not explicitly included in this equation but biomass investments in stem material will typically be reflected in shoot stiffness and thus plant shape (Bouma et al., 2010). To account for reconfiguration in Eq. 1, the parameters C_D, *A*, β or a combination of these three have been used. Statzner et al. (2006) for instance propose to change C_D and/or *A* to account for plant reconfiguration, while Denny and Gaylord (2002) suggest the maximum projected area to be a constant *A* and to reflect shape changes in C_D and β. Luhar and Nepf (2011) have argued that plant posture, i.e. the flow-dependent position of the plant and all its components within the water, affects streamlining and frontal area and express this change through an 'effective leaf length'. They thus advocate constant C_D and β and propose *A* to be the product of a constant characteristic width and a variable effective leaf length. In addition to having only one variable parameter, the latter model has the advantage that all necessary parameters can be derived from material properties and flow measurements and do not require knowledge of plant posture. However, the model has so far only been validated under unidirectional flow.

From the existing data, it appears that vegetation stiffness (and resulting frontal area for any given applied force) and biomass are both key drivers in wave attenuation and associated drag forces. However, their respective relative importance in determining drag force and their potential interactions are not yet well understood. In order to unravel these relationships and improve the assessment of drag forces based on vegetation parameters, we conducted controlled experiments with plant mimics - in the form of flexible plastic strips - under a range of wave conditions. These strips were combined in such a way, that we maintained either (i) a constant frontal area, but with varying biomass (i.e., same number of strips but with different thickness; 8 × 1 mm strips vs. 8 × 2 mm strips), (ii) an identical biomass, but a contrasting frontal area (i.e., few thick strips or more thin strips to obtain a constant volume; 8 × 1 mm strips, 4 × 2 mm strips or 2 × 4 mm strips) or (iii) an identical stiffness between shoots, but a contrasting frontal area (i.e., contrasting numbers of identical strips; 4 × 2 mm strips vs. 8 × 2 mm strips). Moreover, we used the obtained data to evaluate whether or not the model based on effective leaf length (Luhar and Nepf, 2011) is also applicable to drag forces under the oscillatory motion of waves. While we appreciate that coastal vegetation is often exposed to breaking waves in the swash zone, we limited our tests to non-breaking waves. This approach reduces the complexity of hydrodynamics, allowing us to focus on the effect of frontal area, biomass and stiffness of the vegetation elements. For the first time, the direct drag measurements in this study also covered wave loading under extreme events. The measurements reported here will, in particular, help improve existing drag models and, in general, inform future studies on vegetation resilience to high energy wave forcing.

2. Methods

Experiments were carried out in conjunction with tests of wave attenuation over natural salt marsh transplants (Möller et al., 2014). They were conducted in the 5 m wide, 7 m deep and approx. 310 m long Large Wave Flume (GWK) of the Forschungszentrum Küste (FZK) in Hannover, Germany.

2.1. Model setup

An elevated test section of 60 m length was constructed approx. 95 m from the wave paddle which raised the salt marsh and drag sensors 1.5 m above the flume floor. This was necessary to ensure sufficient water depth at the wave paddle to generate the desired waves and to allow waves to fully develop before reaching the test section. At the beginning of the test section, a concrete ramp with a slope of 1:1.7 for 1.2 m, followed by a slope of 1:10 over a distance of 7 m, was installed to allow for a smooth transition of waves (Fig. 1a). Here waves shoaled, but did not break, before interacting with the strip arrangements for all treatments considered here. At the end of the test section, a gravel slope (1:10) was constructed for the same purpose. Wave breaking at the 1:6 asphalt slope at the end of the flume minimised wave reflection and active wave absorption of the wave maker was employed for the same purpose.

On the level test platform, 7.15 m away from the front edge, five drag sensors were deployed in a line normal to the direction of wave approach with the sensor heads flush with the flume floor. The drag sensors were installed 30 cm apart starting 106 cm from the flume wall (Fig. 1b). They operated on the principle of a wheatstone bridge (Carrington, 1990; Denny, 1988) and measured forces in two directions up to 10 N (accuracy ± 0.5% F.S., developed by Deltares). They were deployed to capture forces in the direction of, and counter to, wave propagation along the flume. An electromagnetic current meter (EMCM) was also deployed on the same cross-section, located 76 cm from the flume wall (Fig. 1b). The EMCM was set to record point measurements