



Vegetation-wave interactions in salt marshes under storm surge conditions



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ARTICLE INFO

Article history:

Received 15 November 2015

Received in revised form

16 December 2016

Accepted 19 December 2016

Available online 9 January 2017

Keywords:

Wave dissipation

Flow reduction

Coastal wetlands

Biophysical plant properties

Plant breakage

Vegetation resilience

Wave flume experiment

Cauchy number

ABSTRACT

Vegetation-wave interactions are critical in determining the capacity of coastal salt marshes to reduce wave energy (wave dissipation), enhance sedimentation and protect the shoreline from erosion. While vegetation-induced wave dissipation is increasingly recognized in low wave energy environments, little is known about: (i) the effect of vegetation on wave dissipation during storms when wave heights and water levels are highest; and (ii) the ability of different plant species to dissipate waves and to maintain their integrity under storm surge conditions. Experiments undertaken in one of the world's largest wave flumes allowed, for the first time, the study of vegetation-wave interactions at near-field scale, under wave heights ranging from 0.1–0.9 m (corresponding to orbital velocities of 2–91 cm s⁻¹) and water depths up to 2 m, in canopies of two typical NW European salt marsh grasses: *Puccinellia maritima* (*Puccinellia*) and *Elymus athericus* (*Elymus*). Results indicate that plant flexibility and height, as well as wave conditions and water depth, play an important role in determining how salt marsh vegetation interacts with waves. Under medium conditions (orbital velocity 42–63 cm s⁻¹), the effect of *Puccinellia* and *Elymus* on wave orbital velocities varied with water depth and wave period. Under high water levels (2 m) and long wave periods (4.1 s), within the flexible, low-growing *Puccinellia* canopy orbital velocity was reduced by 35% while in the more rigid, tall *Elymus* canopy deflection and folding of stems occurred and no significant effect on orbital velocity was found. Under low water levels (1 m) and short wave periods (2.9 s) by contrast, *Elymus* reduced near-bed velocity more than *Puccinellia*. Under high orbital velocities (≥ 74 cm s⁻¹), flattening of the canopy and an increase of orbital velocity was observed for both *Puccinellia* and *Elymus*. Stem folding and breakage in *Elymus* at a threshold orbital velocity ≥ 42 cm s⁻¹ coincided with a levelling-off in the marsh wave dissipation capacity, while *Puccinellia* survived even extreme wave forces without physical damage. These findings suggest a species-specific control of wave dissipation by salt marshes which can potentially inform predictions of the wave dissipation capacity of marshes and their resilience to storm surge conditions.

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1. Introduction

The interaction of vegetation with currents and waves affects a wide range of ecosystem functions of coastal salt marshes including

the reduction of hydrodynamic energy, sediment deposition and erosion and carbon storage (Duarte et al., 2013; McLeod et al., 2011; Möller et al., 1999; Temmerman et al., 2005).

Most knowledge on flow dynamics in and around salt marsh canopies has been acquired under benign hydrodynamic conditions. Field studies have shown a reduction of both unidirectional and wave-induced oscillatory flow within plant canopies that can lead to a decline in bed shear stress and erosion and promote sedimentation (Leonard and Croft, 2006; Neumeier and Amos, 2006a,b; Peralta et al., 2008). Flume and numerical modelling stud-

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ies have highlighted the importance of plant posture and motion as a mechanism for the vegetation-mediated reduction of water velocity and hydrodynamic energy (Bouma et al., 2005; Dijkstra and Uittenbogaard, 2010; Luhar and Nepf, 2011, 2016; Mullarney and Henderson, 2010). When waves advance over a vegetated marsh surface, and water depths are low enough to allow wave-induced oscillatory flow to penetrate into the canopy layer, vegetation interacts with this flow and provides flow resistance. In return, the vegetation experiences drag and re-orientation by wave forces (Mullarney and Henderson, 2010). The drag caused by plants causes a reduction of wave orbital velocities and thus wave height and energy (wave dissipation).

Knowledge of this wave dissipation function has generated high interest in the use of vegetated ecosystems, such as salt marshes, as a cost-effective element of coastal protection schemes. Furthermore, the ability of marshes to track rising water levels as a result of the positive feedbacks between vegetation growth and marsh accretion suggests sustainable protection under accelerated sea level rise (Kirwan et al., 2016). However, few empirical observations of vegetation-wave interactions exist, especially during storm surges when water levels and waves are highest and large amounts of sediment can be transported in suspension to low and high marsh zones (Schuerch et al., 2013; Stumpf, 1983; Turner et al., 2006). Hence it is not clear how canopies of different salt marsh plants vary in their ability to reduce wave orbital velocities and thus in their contribution to wave dissipation and erosion protection. Detailed insights into vegetation-wave interactions are of major importance for salt marsh conservation and management aiming to maximize the sea defence value of marshes as well as for the generation of reliable predictions of the marsh wave dissipation capacity and marsh resilience to storm events. Only with this knowledge will it be possible to successfully incorporate marshes into coastal defence schemes (Anderson and Smith, 2014; Bouma et al., 2014; Möller et al., 2014).

Vegetation-wave interactions, and the resulting wave dissipation, are a function of biophysical plant properties such as flexibility, density, biomass and height as well as hydrodynamic conditions such as incident wave height, wave period and water depth (Anderson et al., 2011; Paul et al., 2016).

Plant flexibility determines how much, and in what way, plants move and hence the magnitude of drag forces experienced (Luhar and Nepf, 2016; Mullarney and Henderson, 2010; Paul et al., 2016). Under wave forcing two types of plant movement need to be distinguished:

Swaying is an oscillatory plant movement throughout the wave cycle with symmetric bending angles in the both directions of water flow under wave motion. Whip-like movement is characterised by a fast flipping over from a short backward bending of the plants, to an extended 'forward' bending and wide stem extension in the dominant direction of wave-induced oscillatory flow (in general the direction of wave travel). The latter motion results in flattening of the canopy, a loss of flow resistance and high orbital velocity for part of the wave cycle. A transition from swaying to whip-like movement can occur for a species when wave height and energy increases, with the point of transition depending on the stiffness of the plant and the ratio of plant height to wave orbital excursion (Manca, 2010; Paul et al., 2012).

Numerical models simulating the motion of flexible aquatic vegetation under wave orbital velocities use primarily two dimensionless parameters to describe plant movement and predict drag forces acting on vegetation: (i) the Cauchy number, Ca , which represents the ratio of the hydrodynamic forcing to the restoring force due to plant stiffness; and (ii) the ratio of plant height to wave orbital excursion, L (Luhar and Nepf, 2016). A value of $Ca < 1$ implies an upright plant posture under wave-induced oscillatory flow, as hydrodynamic forces are much smaller than the restoring force

due to stiffness. When $Ca > 1$, plants start to bend with increasing values of Ca indicating a decrease of flow resistance and drag acting on vegetation due to increasing plant bending under wave forces. For $L > 1$, a swaying plant movement with moderate bending angles can be assumed. When $L < 1$, the high orbital velocities are expected to cause an extended 'forward' bending and a flattening of the canopy and low flow resistance for part of the wave cycle (Luhar and Nepf, 2016), i.e. a plant behaviour typically occurring under a whip-like canopy movement. For flexible aquatic vegetation the buoyancy parameter B , representing the ratio of restoring forces due to buoyancy and stiffness, also affects plant bending (Luhar and Nepf 2011). However, B can be neglected in the case of the terrestrial salt marsh plants that exhibit high stiffness compared to seagrasses or macroalgae (Rupprecht et al., 2015a).

Salt marsh plants show a wide variability of stem flexibility, both between different species and the different stem parts of specimens of one species. Little is known on how this variability affects vegetation-wave interactions (Rupprecht et al., 2015a). Previous studies on plants of tidal marshes (Bouma et al., 2005; Heuner et al., 2015; Silinski et al., 2015) but also on freshwater macrophytes (Aberle and Järvelä, 2013; Robioneck et al., 2015; Sand-Jensen, 2003) and macroalgae (Gaylord and Denny, 1997; Stewart, 2006) have shown that drag experienced by plants under hydrodynamic forcing is inversely related to their flexibility. Flexible plants show an avoidance strategy and minimize the risk of folding and breakage through reconfiguration; stiff plants by contrast maximize the resistance to physical damage (tolerance strategy) but may break if hydrodynamic forces increase beyond a critical level (Heuner et al., 2015; Puijalon et al., 2011; Silinski et al., 2015). For plants characterised by swaying movement, a positive correlation between stem stiffness and vegetation-induced wave dissipation has been observed (Bouma et al., 2005). When comparing two salt marsh grasses with different stem flexibility and stem density, Bouma et al. (2010) found that an increase in stem density and biomass can counteract the reduced wave dissipation capacity of flexible plants.

Apart from stem flexibility, density and biomass, the wave dissipation capacity of salt marsh canopies is affected by the ratio of water depth to canopy height (submergence ratio) (Möller et al., 1997; Möller et al., 1999; Yang et al., 2012). The effectiveness of vegetation in dissipating waves has been shown to increase with the percentage of the water column that it occupies, i.e. with decreasing submergence ratio (Augustin et al., 2009; Paul et al., 2012).

Beyond a critical combination of orbital velocities and water depth, changes in type and magnitude of vegetation-wave interactions are likely to result in a significant alteration of vegetation-induced wave dissipation. The existence of hydrodynamic thresholds determining the transition from wave regimes with vegetation-induced wave modification and wave dissipation to those regimes characterised by a flexing, folding or breakage of plants under wave orbital velocities and a decline in vegetation-induced wave dissipation has been suggested by various authors (Gedan et al., 2011; Koch et al., 2009; Möller et al., 1999; Yang et al., 2012), but remains to be demonstrated. This is because the quantification of such hydrodynamic thresholds either by field studies, flume experiments or by numerical modelling is extremely challenging. Field studies suffer from the unpredictable nature and high temporal variability of wave conditions and difficulties in deploying instrumentation under higher energy wave events. Laboratory flume studies offer controlled wave conditions, but are often hampered by limits to the water depths and waves that can be generated. It has proved difficult to build realistic small-scale physical models of vegetated surfaces (Fonseca and Calahan, 1992; Mendez and Losada, 2004).

Numerical models of wave dissipation can simulate a wide range of wave conditions (Mendez and Losada, 2004; Riffe et al., 2011)

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