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Large-scale 3-D experiments of wave and current interaction with real vegetation. Part 1: Guidelines for physical modeling

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ABSTRACT

The growing interest in incorporating nature-based solutions and ecosystem services as part of coastal protection schemes has recently increased in the literature and focused on the understanding and modeling of wave and current interactions with natural coastal landforms, such as salt marshes. With this purpose, using flumes or basins has been one of the preferred options in experimental modeling under controlled conditions. However, due to the inherent complexities associated with this approach, most of the previously published experiments are based on wave-flume experiments using vegetation mimics. The current demand for understanding the relevant processes requires a step forward, which includes experimental modeling with real vegetation on both a relevant large scale and at a sufficiently large water depth. In response to foreseen needs, this study provides useful guidance based on the experience gained from a unique set of experiments conducted in a large wave basin, including wave and current interaction with real salt marsh vegetation. This study reports on plant collection and growing strategies, plant properties, physical set-up, instrumentation, and experimental strategy and dismantling, providing guidelines aimed at being helpful for future experimental efforts at the interface of engineering and ecology.

1. Introduction

In the present era of global change, sustainable coastal protection is of growing importance. Hence, knowledge regarding the mitigation of flooding and erosion hazards with low environmental impact structures is of great interest (Duarte et al., 2013; Möller et al., 2014; Temmerman et al., 2013). Coastal vegetation, such as salt marshes, can play an important role in dissipating energy from waves and currents. They provide services with a high ecological and economical value (Costanza et al., 1997), which is partly related to their capacity to dissipate hydrodynamic energy (Millennium Ecosystem Assessment; United Nations, 2005; Nagelkerken, 2000; Valentine and Heck, 1999). Ecosystem services (ES) is the term applied to describe the benefits human populations obtain from ecosystem functions (Millennium Ecosystem Assessment, 2005). An increasingly recognized but not fully understood service provided by coastal ecosystems is their ability to contribute to coastal protection by attenuating waves, stabilizing shorelines and reducing flood-surge propagation (Bouma et al., 2014). All of these abilities will be relevant in the coming decades due to the potential of increasing storminess and rising sea levels (FitzGerald et al., 2008; Gedan et al., 2010).

The ability of tidal salt marshes to attenuate wave energy has been broadly studied (Asano and Setoguchi, 1996; Barbier et al., 2008; Knutson et al., 1982; Koch et al., 2009; Möller, 2006; Wayne, 1976), and this ability has been shown to have great importance for coastal defense (Barbier et al., 2008; Koch et al., 2009; Leggett and Dixon, 1994; Möller et al., 1999; Yang et al., 2008). Attenuating hydrodynamic energy is also essential for tidal marshes to follow the rising sea levels by accreting sediment (Leonard and Reed, 2002; Bouma et al., 2005a; Wang et al., 2006; Yang et al., 2008). Hence, from the perspective of both coastal defense and nature conservation, an in-depth understanding of the way wave and current energy is attenuated by salt marshes is necessary. Although a large number of studies in the literature analyze currents in tidal wetlands (e.g., Leonard and Luther, 1995; Leonard and Reed, 2002; Shi et al., 1995; Allen, 2000; Christiansen et al., 2000; Neumeier and Ciavola, 2004; Bouma et al., 2005b; and references therein) or characterize wave attenuation (Knutson et al., 1982; Möller et al., 1996; Wayne, 1976; Yang et al., 2008), only a few have focused on studying the attenuation that combines the action of waves and currents (Li and Yan, 2007; Maza et al., 2015; Ota et al., 2004; Paul et al., 2012).

Although most works in the literature have focused on addressing the energy damped by salt marshes, it is difficult to draw generalizations due to the difficulty of reproducing realistic hydrodynamic conditions in laboratory facilities for waves and currents acting together.

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Moreover, a realistic representation of the mechanical behavior and geometric characteristics of plants by means of mimics is difficult to accomplish. In the field, vegetation characteristics and hydrodynamic conditions cannot be properly controlled (Yang et al., 2008; Ysebaert et al., 2011). The results are affected by local conditions, and it is difficult to draw generalizations. Moreover, seasonal biomass changes are highly relevant, particularly in tidal salt marshes located in the temperate NE Atlantic zone, where the aboveground plant biomass is partly or completely lost during winter, which clearly affects plants' efficiency to dissipate energy from waves and currents. In contrast, flume experiments have led to generalizations by showing that wave damping by salt marshes is strongly affected by plant traits, such as rigidity, and by vegetation characteristics, such as vegetation density and standing biomass (e.g., Bouma et al., 2005a, 2010). Similarly, for submerged aquatic vegetation, biomass is a dominant factor in explaining vegetation wave-attenuating capacity (e.g., Penning et al., 2009, for macrophyte species). In addition, a recent study on seagrass surrogates showed that imposing currents on top of waves strongly reduces the wave-attenuating capacity of vegetation and that the magnitude of this effect depends on shoot stiffness (Paul et al., 2012). However, the vegetation structure, plant biomass and traits that determine shoot stiffness differ strongly among coastal plant communities (pioneer zone, lower and upper salt marsh). Wave attenuation is therefore expected to vary across communities and plants (Bouma et al., 2005a, 2010).

Consequently, the role of vegetation structure in terms of wave attenuation remains relatively poorly understood, and modelers lack sufficient experimental data to validate their models across vegetation types. It seems essential to use real vegetation to obtain realistic results to enhance the current understanding of the ecological trade-offs associated with plant-growth strategies. The use of mimics (based on plastic or flexible materials) or idealized vegetation (cylinders) is present in the literature (Anderson and Smith, 2014; Augustin et al., 2009), but this strategy falls well short of providing realistic results. Although scaling laws to preserve plants' mechanical conditions are used (Ghisalberti and Nepf, 2002), it is difficult to find materials to represent both geometrical (shoot-and-leave structure) and mechanical (bending and stiffness) properties, in accordance with a hydraulic scaling. Open questions regarding the use of surrogates in laboratory experiments arise, such as the geometrical representation of the plants (constant or variable height, width and thickness), the spatial distribution of the plants (regular and/or random arrangements) or a plant-fixing system to the bed (reproduction of the root characteristics: rigid or flexible). Moreover, the number of experiments using real vegetation under controlled flow conditions in a laboratory is low, primarily due to the difficulty of using and/or obtaining plants. Collecting seed, growing plants, keeping plants alive and monitoring plants' properties during the experiments are not easy tasks to solve.

The present contribution demonstrates a methodology to perform the eco-hydraulic modeling of salt marshes using real vegetation to determine the efficiency of plants in dissipating energy from waves and currents. The novelty of the experimental work presented here is the study of three-dimensional wave and current interactions with real salt marshes, using both collinear and non-collinear waves and currents. Two different salt marsh species are considered due to their different biomechanical properties and standing biomass, and they both can act as pioneer species in estuaries (Bouma et al., 2010): *Spartina anglica* and *Puccinellia maritima*. The methodology proposed for conducting experiments with living plants in a basin covers different steps, from the collection and growth of the plants to performance of the experiments. Although guides are already available in the literature that note the more important factors to consider (e.g., Frostick et al., 2014), the present work is also a case study in which the methodology is successfully applied. The main objective is to provide a general methodology to run experiments with living plants, and it considers both waves and current conditions, with the aim of extending understanding from both ecological and engineering perspectives.

This study is organized as follows. Section two is devoted to the identification of the experimental needs to perform experiments with real vegetation. Section three focuses on detailing the methodology, covering both practical and technical issues for the experiments presented here. The physical set-up, including the details regarding the flow conditions and the measurements, is introduced in section four. Section five presents a proposed set of recommendations based on the experience gained from the experiments. Finally, conclusions are drawn in the last section.

2. General considerations for the use of real plants in wave-basin experiments

When planning wave-basin experiments with living plants, a series of initial considerations must be made in order to analyze the feasibility and the quality of the data obtained from experiments. In the present study, the conceptual aim of the experiments was to analyze the wave-damping and flow alterations due to wave and current interactions with salt marsh vegetation patches/meadows considering the effect of different hydrodynamics, plant traits and meadow characteristics. Large-scale basin experiments using real vegetation were the preferred option to: 1) consider the collinear and non-collinear waves and currents, 2) avoid possible scale effects and 3) overcome the well-known limitations inherent to the use of mimics (Frostick et al., 2014). When addressing our overall objective, a number of important relevant questions arose:

- the selection of the most appropriate species for the experiments,
- the source, amount and survivability of the selected plants,
- the suitability of the substrate to host a meadow,
- the definition of the experimental set-up to simulate close-to-nature conditions,
- the plant degradation throughout the development of the hydraulic experiment,
- the hydraulic characteristics to be tested during the experiments (water depth, waves and currents),
- the plant response to hydraulic loading,
- the information to be collected from the experiments relative to the plants (physical and mechanical variables),
- the hydrodynamic variables to be collected and the measuring techniques and recoding equipment to be used to slightly interfere with hydrodynamics and plant behavior, and
- the logistics and operation to conduct a large-scale experiment using real vegetation.

It is difficult to summarize all of the different open questions presented during the experiments because options may vary according to the species tested, the characteristics of the facility and the previous experience. However, the set of issues found to be the most relevant are addressed in this section. Although some of them have been treated in Frostick et al. (2014), in the current study, general guidance is given for application to a real case.

2.1. Growing or collecting

After the plant species have been selected, the question of whether plants should be grown on site or collected from nature is likely the first question to answer (see sketch in Fig. 1). Both possibilities possess advantages and disadvantages, and the expenses should not be underestimated. Therefore, the choice for the planned experiment may vary by case.

2.1.1. Growing

To develop a growing scheme, a number of steps needs to be followed to answer the questions of where, when and how to conduct