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Solitary wave attenuation by vegetation patches

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ABSTRACT

The effect of vegetation patchiness on solitary wave propagation, attenuation and wave-induced forces is studied both experimentally and numerically. Vegetation patchiness is simulated with rigid cylinder configurations built by one, eight and four patches tested under emergent, near emergent and submerged conditions. These configurations are parameterized by means of a new parameter (equivalent length, *Le*), which is used to relate cylinders distribution with wave attenuation capacity. This new parameter allows comparing results for the three patches configurations. Larger attenuation rates are found for higher wave heights and shorter wave periods. The influence of water depth is also considered by means of the submergence ratio (*SR*) in order to account for the percentage of water column affected by vegetation. Higher attenuation rates are obtained for emergent conditions. High correlations are found between wave attenuation and a new set of parameters, the depth wave number ($kLe \times SR$), that accounts for submergence conditions and field characteristics and a new Reynolds number (Re_s^{Le}), that is calculated considering the field vegetation dimensions affecting the flow. Experimental results are extended using IHFOAM, a three dimensional Navier-Stokes equations solver, to analyze wave forces on individual cylinders and wave propagation patterns showing the variability of forces magnitude and direction associated to vegetation patchiness.

1. Introduction

Coastal protection provided by vegetation has long been a topic of interest. The interaction of flow with vegetation plays an important role in coastal protection (Costanza et al., 1997; Borsje et al., 2011; Temmerman et al., 2013; Hashim et al., 2013; Duarte et al., 2013; Ondiviela et al., 2014) and also affects many ecological processes, such as sediment transport (Chen et al., 2007; Bouma et al., 2007) or the supply of dissolved nutrients (Cornelisen and Thomas, 2004) among others. Sea level rise and the increase in the frequency and intensity of extreme events related to climate change contribute to higher erosion and flooding risks in coastal areas (Wong et al. 2014). Coastal vegetation systems are starting to become an essential option in ecosystem based adaptation or as so-called nature based solutions for both adaptation and risk reduction in coastal areas (Barbier et al., 2011; Narayan et al., 2016). For that reason, many experimental and numerical studies have been developed to characterize and quantify protection efficiency of vegetation systems. Most of them are focused on wave attenuation produced by vegetation fields under controlled flow conditions, especially using laboratory experiments with solitary waves (Huang et al., 2011; Strusinska-Correia et al., 2013; Maza et al. 2015) and emergent cylinders. However, previous studies, such as Nepf (1999) and Augustin et al. (2009), have pointed out that varying submergence ratios lead to different flow regimes.

Moreover, vegetation field properties strongly determine the ecosystem wave attenuation capacity. A wide range of vegetation species can be found in coastal areas with completely different characteristics. Several studies on the interaction of flow with vegetation have been carried out attending to individual plant characteristics such as flexibility (Luhar and Nepf, 2011; Paul et al., 2012; Ozeren et al., 2013), vegetation density (number of shoots per square meter) (Luhar et al., 2008; Bouma et al., 2010) or shoots distribution in the interaction of flow and vegetation shoots distribution (Tanino and Nepf, 2008; Maza et al. 2015). However, only few have been focused on vegetation patchiness. Vegetation fields in nature are not uniform and continuous. Many intertidal ecosystems present flow channels between vegetation patches or non-uniform fields due to changes in substratum or human action, among others. Therefore, there is a need to explore the role of vegetation patchiness on wave attenuation. Using small-scale experiments Fonseca et al. (1983); Folkard (2005) and Fonseca and Koehl (2006) analyzed mean and turbulent flow patterns for seagrass patches under uniform flow conditions. Vandenbruwaene et al. (2011) carried out a set of experiments testing Spartina patches under uniform flow conditions. They showed that flow acceleration next to the vegetation patches depends on the

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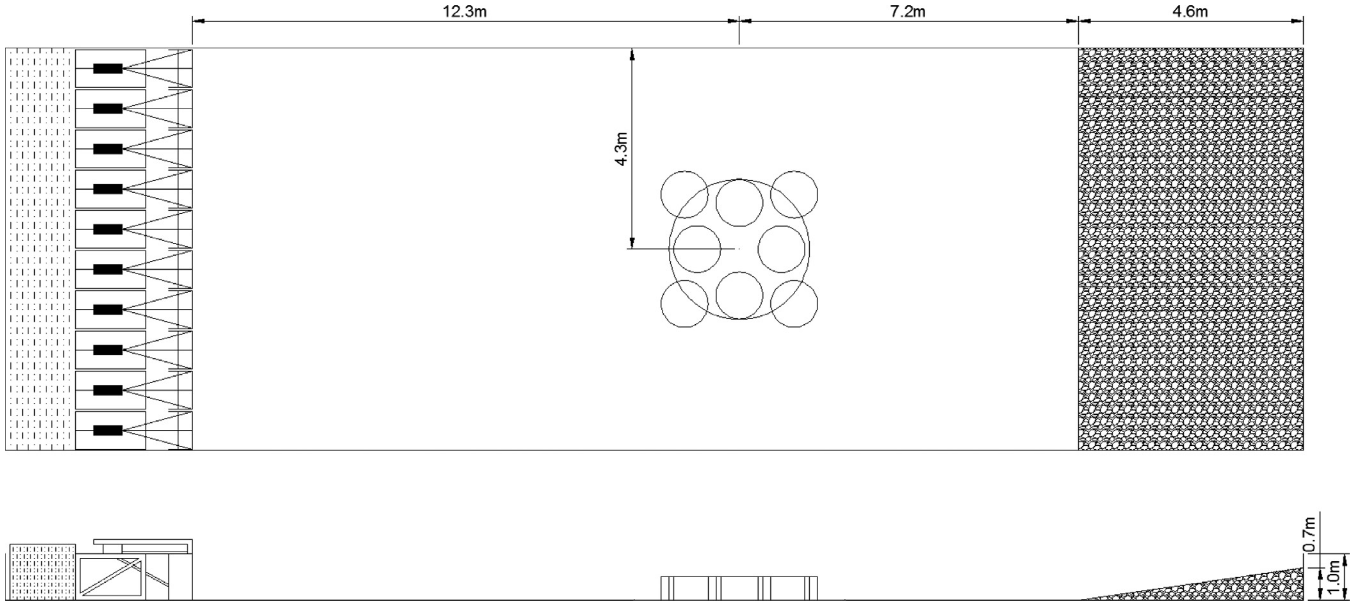

Fig. 1. Wave basin and location of the three cylinder configurations. Top (upper panel) and lateral (lower panel) views.

distance between them. Flow patterns developed in and around a finite patch formed by cylinders have been also studied (Zong and Nepf, 2010) in order to characterize the flow and its implications on sediment and nutrients deposition. Later, Kondziolka and Nepf (2014) studied the wake interaction behind vegetation patches under unidirectional flow considering different patches distances and densities. Recently, Irish et al. (2014) conducted laboratory experiments to evaluate the tsunami run-up reduction by vegetation patches. However, the influence of patchiness on wave attenuation remains unstudied, demanding higher scale experiments, including variable patchiness, to get a deeper understanding of its role on wave attenuation.

As a first step, in this work we aim at understanding the role of vegetation patchiness on solitary wave propagation considering a combination of experimental and numerical modeling. A new set of experiments is conducted considering three different patches distribution under varying water depths. Vegetation patchiness is modeled by means of three vegetation field configurations consisting of one, eight and four patches built of rigid vertical cylinders. Experimental results are analyzed and discussed in terms of wave parameters, submergence ratio and field characteristics and extended next using a three dimensional CFD model. Parameterizations in terms of new non-dimensional numbers are formulated to include the effect of patchiness on wave dissipation. Numerical results provide wave patterns and forces exerted on individual cylinders. Experimental set-up and tests are described in Section 2 while Section 3 is devoted to present and discuss the attenuation results obtained for the different tests. Section 4 shows the numerical analysis including the description of the numerical domain and the obtained results. Finally, conclusions are summarized in Section 5.

2. Experimental set-up

Experiments were conducted in the Directional Wave Basin at the University of Cantabria, Spain. The wave basin is 8.6 m wide, 1.0 m deep and has an effective length of 24.1 m. The experimental setup is shown in Fig. 1. The lateral boundaries are vertical walls. The left end is equipped with a piston-type wavemaker including 10 paddles that can move independently. The wavemaker stroke is 90 cm. At the right end a gravel beach is built to dissipate the incoming waves. Three different cylinder configurations were tested in the experiments. The center of these configurations was located at 12.3 m from the wave paddles mean position in the x direction and centered in the transversal direction (Fig. 1).

The three cylinder configurations considered in the experiments were built using wood cylinders. A platform was fixed to the basin bottom with a sufficient number of holes to screw the cylinders to conform the three configurations saving time when changing configurations during the experiments. This platform was located at the center of the wave basin, at 4.3 m from the vertical walls. This allowed having a study area with negligible effects of the vertical boundaries and large enough to shape different field configurations. Cylinders were 3 cm in diameter, 50 cm tall and uniformly distributed with a 9 cm separation between centers. For the first configuration (C1), 880 cylinders were disposed in a single 3 m diameter circular shape whereas the second configuration (C2) was composed of 8 circular cylinder patches of 1 m diameter each. Each patch was made of 112 cylinders leading to a total number of 896. The third configuration (C3) was formed by the four inner patches of the second configuration. Fig. 2 shows cylinders distribution for the three configurations.

These three configurations were selected in order to study the influence of having vegetation patches instead of a continuous field. C2 was built of almost the same number of cylinders as C1 but shaping eight individual patches. The location of these patches was selected aiming at covering the available drilled area with a minimum distance between patches allowing the development of flow preference channels. C3 was chosen based on C2 but using half of the cylinders resulting in different preference channels.

In order to analyze the influence of submergence ratio, defined as the ratio between vegetation height and water depth, emergent, nearly-emergent and submerged conditions were tested considering three different water depths, h = 0.30, 0.50 and 0.62 m, respectively. Further submerged conditions were not tested due to basin depth limitations.

A series of wave gauges (18 resistive and 11 ultrasonic) sampling at 50 Hz were distributed around and inside the different patches in order to measure free surface, Figs. 2 and 3. Gauges location remained the same (Table 1) for all the tests, allowing comparable measurements for all three configurations.