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Wave attenuation over porous seabeds: A numerical study

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ABSTRACT

We investigate wave attenuation over porous seabeds by means of a phase- and depth- resolving numerical model that solves the Volume-Averaged Reynolds-Averaged Navier–Stokes (VARANS) equations. The numerical model is calibrated with laboratory data from Corvaro et al. (2010). The numerical model predicts the wave attenuation and the velocity field near the porous bed for different regular wave conditions. Subsequently, a parametric analysis on the physical characteristics of the porous media is made to investigate their relative role on wave attenuation. The results of the analysis indicate nonlinear dependencies of wave attenuation on both, total porosity and mean grain diameter. The widely used parabolic model in terms of the dispersiveness parameter predicts both types of dependencies, effectively. Hence, new parametric formulations are derived for the determination of the coefficients involved in the parabolic model for each type of dependence. On the other hand, the role of the spectral shape on the wave spectrum bulk dissipation is investigated. Numerical results for irregular waves show a clear dependence of the dissipation rate with the Ursell (Ur) parameter. The dissipation rate becomes sensitive to frequency spreading for $Ur < 20$. Moreover, forcing the model assuming an f^{-5} tail in the incident wave spectrum underpredicts seabed attenuation with respect to an f^{-4} formulation. Finally, bispectral analysis of irregular wave propagation allow us to investigate the mechanism of wave attenuation. The numerical results suggest that energy is directly dissipated at the peak frequency, whereas nonlinear energy transfer plays an important role in energy attenuation at higher harmonics.

1. Introduction

The interaction of waves with either permeable structures or the seabed is a classic problem of coastal engineering. Over the years numerous experimental, theoretical and numerical studies have been performed to characterize the damping of water waves over a porous medium.

Experimental studies were dedicated mainly to the analysis of the wave damping over permeable structures, while only few experiments focused on the wave attenuation over a permeable seabed (e.g. Savage, 1953; Sawaragi and Deguchi, 1992; Corvaro et al., 2010). Within a general analysis of innovative methods for the dissipation of coastal water waves (e.g. Lorenzoni et al., 2010; Postacchini et al., 2011), the laboratory experiments of Corvaro et al. (2010)'s were performed to study the propagation of waves over different kinds of bed: smooth, rough (both impermeable) and porous (permeable) beds. By comparing the wave dissipation over a rough impermeable seabed and a rough permeable seabed, they found that the larger dissipation occurring when waves propagate over a permeable seabed is mainly due to the flow resistance inside the porous medium. More recently, Corvaro et al. (2014) carried out an experimental study of the internal flow kinematics of waves that propagate on different types of beds, focusing both on the nearbed dynamics induced at a porous bed and on the analysis of the relationship between the wave height and the internal flow attenuation.

The simplest analytical models available make use of the Laplace equation for the flow in the free-fluid region and of Darcy's law to describe the flow through the porous medium. Liu and Dalrymple (1984) improved the modeling of the flow within the porous seabed by using Dagan's equation and by adding an acceleration term to represent the flow unsteadiness in the permeable bed. However, the effects due to the added mass were not accounted for in their model. Instead, Gu and Wang (1991)'s model employed the extended Forchheimer's equation to describe unsteady porous flows: the nonlinear effects of both turbulent and

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inertial resistances were included, hence, their model is valid for a wide range of permeabilities, however, the resistance coefficient is linearized. The porous flow theories used in Liu and Dalrymple (1984)'s and Gu and Wang (1991)'s analytical models are simplified to become Laplace's equation for the dynamic pore pressure.

The flow through porous media can be simulated using either microscopic or macroscopic approaches. The former requires the individual description of the 3D individual elements using a very high mesh resolution to describe the flow within the elements. Dentale et al. (2014) simulated wave-structure interaction considering different elements. Nevertheless, simulating the detailed flow between the element is not practical for coastal engineering applications at prototype scale (Losada et al., 2016). On the other hand, the macroscopic approach provides a means to estimate the mean flow within the porous media using spatial averaging and the coupling between two flow models (i.e., inside and outside the porous media) and matching conditions at the interface. This approach has been widely employed in the numerical modeling of wave-structure interaction.

Numerical models are most often based either on the Nonlinear Shallow Water Equation (e.g. Wurjanto and Kobayashi, 1993; Van Gent, 1995a), on Boussinesq-type equation (e.g. Cruz et al., 1997) or on the Reynolds Averaged Navier Stokes equations (e.g. Karunarathna and Lin, 2006). The flow in the permeable bed is modeled with different approaches in the various existing models: Van Gent (1995a) and Hsu et al. (2002) considered the extended Forchheimer's equation and added a convective term with the inclusion of unsteady effects on the Volume-Averaged/Reynolds-Averaged Navier Stokes (VARANS) approach; Hsiao et al. (2002) used Euler's equation and added a resistance force due to the porous medium that consists of inertial, linear and nonlinear drag contributions. Volume averaging allows for a proper description of small-scale turbulence effects in the porous media and hence has been successfully validated against different data sets (e.g., Hsu et al., 2002; Lara et al., 2006; Losada et al., 2008; Pintado-Patiño et al., 2015; among many others). For instance, Lara et al. (2011) employed the VARANS approach for the study of breaking solitary wave evolution over a porous step finding that wave breaking dominates over seabed dissipation, whereas Pintado-Patiño et al. (2015) studied the swash zone boundary layer dynamics on a permeable beach.

The present contribution aims at exploring the capabilities of the VARANS-COBRAS model of Hsu et al. (2002) in the representation of the dissipation of water waves that evolve over a porous seabed. Hence, the proposed analysis provides a detailed benchmarking of the model of interest on the basis of the detailed and comprehensive experimental dataset of Corvaro et al. (2010, 2014). This dataset includes a large number of regular wave sizes (i.e. breaking and non-breaking) and shapes (i.e. weakly and highly skewed) each of them properly characterized in terms of wave height attenuation in space and both internal and nearbed kinematics, captured by means of dedicated PTV measurements. Hence, such a dataset provides the ideal basis for an overall evaluation - including wave height decay, free-surface motion, and nearbed kinematics - of the VARANS-COBRAS' capabilities of reproducing waves evolving on a porous seabed.

The paper is made of 6 sections. Following the present Introduction, Section 2 illustrates the experiments (setup and dataset) used for the proposed benchmarking, while the fundamentals of the numerical model are given in Section 3. The main results of the analysis, including model-data comparisons and parametric analyses on the specific roles of seabed permeability and mean diameter, are given in Section 4. Furthermore, irregular waves simulations allow to investigate the role of frequency spreading. The role of nonlinear energy transfer on wave attenuation is discussed in Section 5. Finally, a summary of the main findings is presented in Section 6.

Table 1
Wave characteristics from Corvaro et al. (2010).

Wave	H_p (cm)	T (s)	H_u (cm)	ε	Ur
A	3.6	1.0	2.8	0.09	1.98
B	3.6	1.5	3.1	0.10	6.37
C	5.0	1.5	4.3	0.14	8.74
D	10.0	1.5	8.8	0.29	17.79
E	10.0	2.0	9.6	0.32	37.61
F	10.0	2.5	11.3	0.38	72.14
G	15.0	2.0	16.0	0.53	63.03

2. The experimental setup

The data used for the model validation/calibration correspond to the laboratory experiments performed by Corvaro et al. (2010, 2014) at the wave flume of the "Laboratorio di Idraulica e Costruzioni Marittime" of the "Università Politecnica delle Marche" (Ancona, Italy), and, hence, only a general overview is here provided. The wave channel is 50 m long, 1 m wide and 1.3 m deep (see Fig. 1). The waves were generated by a piston-type wavemaker operated with no active wave absorption. However, a wave-absorbing mattress was placed at the opposite end of the flume with the function to reduce the wave reflection from the vertical rigid end-wall (Fig. 1).

Table 1 shows the wave characteristics (wave height at the paddle H_p, wave period T, wave height at the upstream section of the model H_u, nonlinearity $\varepsilon = H_{S4}/h$ and Ursell parameter $Ur = H_{S4}L^2/h^3$ where h is the water depth and H_{S4} the wave height at the wave gauge located before the porous media) of the regular, non-breaking waves, used in the present study. Waves were generated on a depth of 0.51 m, then propagated on a ramp, with slope 1:15, up to a water depth h of 0.30 m. Once arrived on the horizontal bottom, waves run on an impermeable bed (made of steel plates above wood platforms) for a length of 4.5 m, then on the porous model, which was 6 m long, and, again, on an impermeable bed. A minimal distance of about 15 m was placed between the wavemaker and the model to allow for a smooth wave formation process. The 6 m long model was made of three different rigid bed configurations: a smooth, a rough (both impermeable) and a porous (permeable) bed. Both the rough impermeable bed and the permeable bed were made of impermeable plastic spheres of mean diameter $d_{50} = 0.036$ m filled with sand to make them sink. The porous medium was composed of 6 layers of spheres with total thickness h_0 of 0.182 m and porosity n of 0.29. The display of the spheres was rhombohedral in order to have the maximum packing, and, hence, the most stable configuration.

The measuring instruments used for the present analysis were 8 electro-sensitive elevation gauges (used to measure the water levels), 2 three-dimensional Acoustic Doppler Velocimeters (ADVs) (employed for the measurement of the flow velocity along two verticals) and a Particle Tracking Velocimeter (PTV) for the flow velocity of wave D, E and G. Fig. 2 shows the locations of the instruments with respect to the porous seabed.

The electro-sensitive elevation gauges were positioned as follows: "S1" just downstream of the wave paddle (water depth of 51 cm), "S2" at the seaward end of the ramp (water depth of 0.51 m), "S3" at the shoreward end of the ramp (water depth $h = 0.30$ m), "S4" seaward end of the model bed ($h = 0.30$ m), "S7" shoreward end of the model bed ($h = 0.30$ m) and "S8" just downstream of the model bed ($h = 0.30$ m). The other elevation gauges placed over the physical model were "S5" and "S6" placed, respectively, 2 and 4 m downstream of gauge "S4". The wave gauge "S7"