Coastal Engineering 91 (2014) 280–298

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Flow dynamics on a porous medium

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ARTICLE INFO

Article history:
Received 4 November 2013
Received in revised form 30 May 2014
Accepted 2 June 2014
Available online 15 July 2014

Keywords:
Porous medium
Kinematics
Nearbed dynamics
Velocity reduction
Energy attenuation

ABSTRACT

In this paper, which can be regarded as a companion of that by Corvaro et al. (2010), experimental results on the internal flow kinematics of waves which propagate on different types of beds, focusing on the nearbed dynamics induced by a porous bed, are illustrated and analyzed. The porous bed induces a major attenuation in the upstream-to-downstream direction of both wave height (≈30%) and internal flow velocity (≈50% for the maximum and minimum phases). The relationship between the wave height and the internal flow attenuation has been analyzed by means of wave energy arguments. We also found that the averaged reduction of mean flow between the smooth and porous-bed cases is approximately of 45% and 55%, respectively, for the horizontal and vertical velocity components. The stronger reduction of the vertical velocity is due to a significant variation of this velocity profile with respect to what occurs on an impermeable bed. An optical technique is used to extract the flow velocity from suitable video images; the wave dynamics on the porous medium is analyzed by evaluating the mean wave flow, the turbulence and the vorticity fields over the layer. The turbulence, indirectly characterized in terms of instantaneous velocity spectra, is found to be largely confined within the bottom boundary layer, located at a position deeper than the peaks of the mean flow. From the analyses of the instantaneous velocity spectra a clear anisotropy and inhomogeneity are found for the nearbed turbulence. This is confirmed by the presence, in the bottom boundary layer, of elongated coherent vortical structures whose intensity is the maximum during the wave crest and trough phases.

1. Introduction

The interactions between the flows propagating in a free-fluid region and those restrained by the resistance of a porous medium are of interest for both engineered fluids and natural streams. Our main interest here is in the interaction of natural streams with a porous medium. More in detail, we focus our attention on the interaction of sea waves with porous media be they artificial (e.g. breakwaters) or natural (e.g. seabeds). Even restraining our attention to water flows typical of the marine environment, the importance of the evolution of flows on a porous medium is widely recognized. Numerous studies have been performed to characterize the wave damping over a porous medium. More experiments were dedicated to characterize the wave damping over a permeable structure than to study the specific features of the flow induced by a porous seabed (e.g. Savage, 1953; Sawaragi and Deguchi, 1992). The interaction of sea waves with either permeable structures (e.g. Losada et al., 1996) or a porous seabed (e.g. Corvaro et al., 2010; Hsiao et al., 2002 and Karunarathna and Lin, 2002) is a classic problem of coastal engineering. Natural seabeds are, usually, composed of permeable layers of sediments that enable mass and momentum transfer across the interface between the free-fluid region and the porous bed. As the flow propagates through the porous medium, resistances act on the fluid due to both fluid viscosity and fluid–particle interactions (Bear, 1972).

The simplest model used to describe the flow through a fixed, uniform and isotropic porous medium is based on Darcy's law, while if the flow becomes turbulent Forchheimer's equation is better suited. Burcharth and Andersen (1995) and Van Gent (1995) discussed in detail the role of the different friction parameters which influence the flow through a porous medium. Moreover, the porous bed alters the structure of the overlaying flow.

Liu and Darlymple (1984) and Gu and Wang's (1991) theories assume that the flow above the porous bed is irrotational and derive a complex wave dispersion relation, which is solved iteratively to calculate the complex wavenumber, and obtain all flow quantities of interest by solving Laplace's equations over and inside the porous medium. More details on this type of modeling can be found in Corvaro et al. (2010).

It is found that when waves propagate on a porous medium the wave height and the mean velocity decrease. The intensity of such a decrease changes with the wave characteristics and with the porous medium properties (length, thickness and permeability).

Dixen et al. (2008) investigated on the wave boundary layer over a bed with large roughness by using the results of a dedicated laboratory campaign. In one group of experiments they used, as roughness elements, regular ping-pong balls with different pattern, packing density and number of sphere layers (and with a diameter equal to that used in our

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http://dx.doi.org/10.1016/j.coastaleng.2014.06.001
0378-3839/

experiments). They found that the boundary layer turbulence is weakly influenced by the pattern, density and roughness of the spheres.

Fundamental for the understanding of the nearbed wave flows are the experimental studies on oscillatory boundary layers occurring over both smooth (e.g. Nielsen, 1992) and rough (e.g. Sleath, 1987) beds. Among recent, interesting works on turbulent oscillatory boundary flows on rough, impermeable beds we find the experiments of Krstic and Fernando (2001) and the numerical simulations of Costamagna et al. (2003) and of Fornarelli and Vittori (2009). During recent years the study of turbulent boundary layers on a porous bed has received much attention. However, most of the studies available in the literature, e.g. the numerical studies of Mendoza and Zhoun (1992), Prinos et al. (2003), Lemos (2005), and Chan et al. (2007), and the experimental studies of Pokrajac et al. (2007), are concerned with the analysis of turbulent boundary layers induced by steady flows on a porous layer.

The work most comparable to the present analysis is the experimental investigation of Lara et al. (2002), which studied wave flows on a porous bed by means of a PIV technique. In the same fashion, we have here used a different non-intrusive technique (i.e. the Particle Tracking Velocimetry).

In view of the scarcity of studies which give a global description of the overall flow dynamics induced by waves propagating on a porous bed (i.e. wave height decay, internal flow dynamics, nearbed kinematics, turbulence, vorticity) we have carried out a complete analysis of such a dynamics and, in conjunction with the analysis of Corvaro et al. (2010), provide a more complete insight into some of the mechanisms linking the various mentioned phenomena. Within a general analysis of innovative methods for the dissipation of coastal water waves (e.g. Lorenzoni et al., 2010; Postacchini et al., 2011), laboratory experiments were, thus, performed to study the propagation of waves over different kinds of bed: smooth, rough (both impermeable) and porous (permeable).

The interaction between the porous bed and the turbulent flow over it, the kinematics of the bottom boundary layer and the dependence of the wave height on the internal flow over each configuration are investigated in the present study. The experimental configuration is described in Section 2. Section 3.1 provides results on the internal flow (i.e. between the top of the bottom boundary layer and the free surface) velocity decay that occurs when the waves propagate over the mentioned bed configurations. In Section 3.2 focus is on the nearbed dynamics induced by a porous bed. We propose the results of the dynamics of waves on a porous medium by evaluating the mean wave flow, the vorticity and the turbulence fields over the layer. Section 4 provides both a discussion of the results and the closure of the paper.

2. The experimental tests

The experimental tests were performed at the "Laboratorio di Idraulica e Costruzioni Marittime" of the "Università Politecnica delle Marche" (Ancona, Italy) that hosts a large wave flume, equipped with a wavemaker, for maritime experimental models at a reduced scale (see Fig. 1). The inside dimensions of the flume are: length of 50 m, width of 1 m and depth of 1.3 m. The sidewalls of the flume are glassed for the central 36 m and enable to view and record (video) the flow from the lateral sides.

2.1. The laboratory setup

The waves were generated by a piston-type wavemaker with a maximum stroke of ± 0.5 m. The wavemaker was operated with no active absorption. 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. The present analysis aims at highlighting the role of a porous bed, hence, breaking waves are not considered because the surface-generated turbulence could obscure too much the whole dynamics. To avoid interpretation difficulties, which might be induced by a random wave field, in the present study we analyzed three non-breaking regular waves (first order theory), the characteristics of which are reported in Table 1: wave height H_0, period T, the wave height at the upstream section of the model H_u, the Ursell parameter $Ur = H_u L^2 / h^3$, the Reynolds number $Re = U_{0max} A / \nu$ (where A is the semi-horizontal oscillation of the fluid particles just outside the bottom boundary layer corresponding to the maximum value of u evaluated at a water depth h over the model, i.e. U_{0max}, ν is the kinematic viscosity, L is the wave length over the model), and the porous medium Reynolds number $Re_{pm} = U_s D_{50} / \nu$ (where D_{50} is the medium grain size of the porous medium made of spheres of a diameter $D_{50} = 3.6$ cm and U_{pm} is the maximum horizontal velocity inside the porous medium, evaluated by applying the model of Gu and Wang (1991) with the resistance coefficients reported in Corvaro et al. (2010)). An analysis of the most important resistance mechanisms inside the porous medium revealed that for the waves reproduced in our experiments all the three main resistance mechanisms (laminar (f_l), turbulent (f_t) and inertial (f_n)) have the same importance, see Fig. 8 of Corvaro et al. (2010). Therefore, the Darcy formula is not suitable because the flow regime inside the porous medium is turbulent, hence the Forchheimer formula needs to be applied to describe the flow inside the porous medium both in the model and at prototype scale.

A reduced geometrical scale of 1:10 has been used. Moreover the wave characteristics are reproduced by using Froude similarity. The ratio between the prototype Reynolds number ($Re_{(prototype)}$) and the model Reynolds number (Re) is $10\sqrt{10}$.

The 6 m-long model was placed on the horizontal bottom of the wave tank (see Fig. 1) and was made of three different bed configurations: a smooth, a rough (both impermeable) and a porous (permeable) bed. The porous medium was composed of 6 layers of spheres (see Fig. 2) with a total thickness h_s of 18.2 cm and a porosity n of 0.29; the rough bed was composed by a single layer of the same spheres. The display of the spheres was rhombohedral in order to have the maximum packing, and, hence, to have the most stable configuration. Other displays can produce different attenuations, because of different porosities.

The water depth h was of 51 cm at the wavemaker, while over the model h was equal to 30 cm (for the configurations of rough and porous beds h was measured from the top of the spheres). For a complete description of the experimental setup and of the porous medium's characteristics see Corvaro et al. (2010).

In order to obtain conditions unaffected by any reflections (the absorbing mattress did not provide complete absorption), the model beds were placed approximately 23 m far from the flume end wall and the final portion of the signals has been neglected. Moreover, undisturbed conditions were reached after a transient of about 8 s during which the wave height ramped up to the regime conditions. Such a

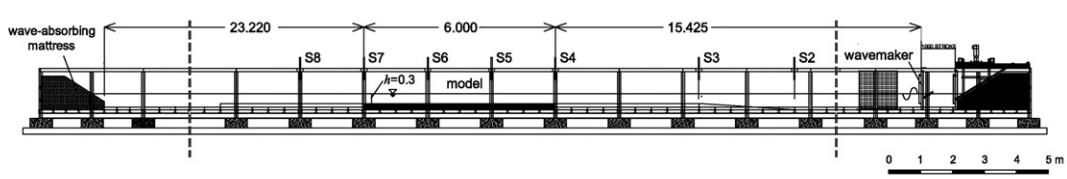

Fig. 1. The wave flume.