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Propagation of solitary waves over a submerged permeable breakwater

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ABSTRACT

We study the interactions between a non-breaking solitary wave and a submerged permeable breakwater experimentally and numerically. The particle image velocimetry (PIV) technique is employed to measure instantaneous free surface displacements and velocity fields in the vicinity of a porous dike. The porous medium, consisting of uniform glass spheres, is mounted on the seafloor. Due to the limited size of each field of view (FOV) for high spatial resolution purposes, four FOVs are set in order to form a continuous flow field around the structure. Quantitative mean properties are obtained by ensemble averaging 30 repeated instantaneous measurements. The Reynolds decomposition method is then adopted to separate the velocity fluctuations for each trial to estimate the turbulent kinetic energy. In addition, a highly accurate two-dimensional model with the volume of fluid interface tracking technique is used to simulate an idealized volume-averaged porous medium. The model is based on the Volume-Averaged Reynolds Averaged Navier–Stokes equations coupled with the non-linear k–ε turbulence closure solver. Comparisons are performed between measurements and numerical results for the time histories of the free surface elevation recorded by wave gauges and the spatial distributions of free surface displacement with the corresponding velocity and turbulent kinetic energy around the permeable object imaged by the PIV system. Fairly good agreements are obtained. It is found that the measured and modeled turbulent intensities on the weather side are much larger than those on the lee side of the object, and that the magnitude of the turbulent intensity increases with increasing wave height of a solitary wave at a constant water depth. The verified numerical model is then used to estimate the energy reflection, transmission and dissipation using the energy integral method by varying the aspect ratio and the grain size of the permeable obstacle.

1. Introduction

Submerged permeable breakwaters are frequently built along the coast to reduce the impact of waves and currents due to their low costs compared to that of impermeable structures and their ability to dissipate more wave energy through viscous dissipation within the porous media. In particular, the raised use of coastal recreation increases the acceptability of submerged-type breakwaters because such underwater structures do not obstruct the view of the ocean, which is important for the aesthetic and environmental considerations of coastal engineers and planners. An understanding of the interaction between water waves and submerged permeable breakwaters is thus vital.

The wave deformation induced by periodic waves propagating over a submerged porous medium has been thoroughly studied using various approaches. For efficient calculation, several depth-integrated numerical models have been developed to study wave transformation or to assess the functional efficiency of porous breakwaters in terms of the wave reflection, transmission and dissipation (RTD) coefficients by solving mild-slope equations (Hsu et al., 2008; Losada et al., 1996), shallow water equations (van Gent, 1994), or Boussinesq equations (Hsiao et al., 2002, 2010). Experimental works, for example those by Losada et al. (1997) and Ting et al. (2004) have examined the porosity effect on the harmonic generation of periodic waves passing over porous structures. In recent years, nonlinear long wave interaction with porous breakwaters has received a considerable amount of attention. In many studies, solitary waves have been used to model certain behavior of nonlinear long waves, such as the leading wave of tsunamis and storm surges (Hsiao and Lin, 2010; Hsiao et al., 2008; Synolakis and Bernard, 2006). In numerical simulation, a solitary wave that has only a single wave crest can be used to study the wave transformation and associated turbulent velocity fields free from the effects of both the preceding and subsequent waves. Under solitary wave forcing, many studies have conducted a detailed estimation of RTD coefficients for emerged-type porous obstacles (Lin and Karunarathna, 2007; Lynett et al., 2000; Silva et al., 2000).

While free surface motion has been extensively investigated in the literature, few studies have considered the dynamic interaction between the structure itself and the induced flow fields, which is important in the design of coastal structures. There are two general ways to obtain more information about velocity fields during the process of wave-structure interaction: direct measurements in a physical laboratory and numerical modeling based on Navier–Stokes-type equations. For the interaction between a solitary wave and a submerged permeable breakwater, Huang et al. (2003) studied the flow fields outside and inside an object using a two-dimensional (2D) unsteady

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Navier–Stokes-type model with the assumption that the flow outside the porous media is laminar. The accuracy of numerical model was verified with experimental data for free surface elevation in time histories provided by Losada et al. (1997). Shao (2010) used the smoothed particle hydrodynamics (SPH) method to solve the porous media module formulated by Huang et al. (2003). Lara et al. (2011) investigated the wave damping on breaking solitary waves passing over an underwater porous shelf using a 2D Volume-Averaged Reynolds Averaged Navier–Stokes (VARANS) model. Model validation carried out by Lara et al. (2011) contained two parts respectively for impermeable step and permeable seabed under water waves. For impervious case, the evolution of solitary wave passing over an underwater impermeable shelf was calculated and the modeled results of free surface in time histories were compared with measurements of Seabra-Santos et al. (1987). For permeable case, monochromatic wave propagation over a permeable bed reported by Sawaragi and Deguchi (1992) was chosen for the validation of porous flow modeling. Both experimental efforts done by Seabra-Santos et al. (1987) and Sawaragi and Deguchi (1992) did perform detailed measurements on the free surface evolutions, but the velocity fields, however, were not the main concern in their reports. Zhang et al. (2012) numerically studied the variations of the flow field around a submerged porous object under a solitary wave by altering the geometry of the obstacle via a 2D VARANS model. However, the model validation in the aforementioned numerical studies was carried out for comparisons with the measured free surface motion induced by periodic water waves over porous underwater step. To the knowledge of the authors, detailed spatial measurements on the flow fields for a solitary wave over a submerged permeable breakwater are still lacking in the literature. Available laboratory measurements on the flow fields of water waves passing over porous breakwaters can be found in the studies by Losada et al. (1995), Sakakiyama and Liu (2001), Garcia et al. (2004), among others. Those studies used the laser Doppler velocimetry (LDV) technique to quantify the velocity and turbulence characteristics around and even inside a permeable breakwater under periodic waves. However, LDV cannot simultaneously capture a large region of the flow fields of interest. The particle image velocimetry (PIV) technique is more suitable for mapping out the spatial distribution of the velocity field in a large flow region. Since the velocity fields (Chang et al., 2001; Lin et al., 2006) and even the turbulent kinetic energy (TKE) fields (Wu et al., 2012b) caused by the interaction of a solitary wave and a submerged impermeable obstacle have been thoroughly measured using PIV, the technique can be applied to flow fields around a submerged porous medium under solitary wave forcing.

The present study conducts comprehensive measurements of solitary wave propagation over a submerged permeable breakwater using a PIV system. Mean data from laboratory experiments are analyzed by the ensemble-averaged method for the time histories of the free surface elevation recorded by wave gauges and spatial distributions of free surface motion with velocity and turbulence properties around the porous media imaged by PIV. We use a viscous numerical wave tank to reproduce conditions identical to those in the experiments in order to model an idealized volume-averaged porous medium using a 2D VARANS model (Hsu et al., 2002; Lin and Liu, 1998a,b). Comparisons between experimental measurements and 2D calculated results are carried out, with satisfactory agreements obtained. The validated 2D numerical model is then used to further explore the functional efficiency of the submerged porous medium under solitary wave forcing by varying the porosity and the length of the breakwater.

2. Research methods

2.1. Experiment

2.1.1. Wave flume setup, measurement apparatus and procedure

Experiments were conducted in a 2D glass-walled and glass-bottomed wave flume at the Department of Hydraulic and Ocean Engineering, National Cheng Kung University. The physical wave tank is 25 m long, 0.5 m wide and 0.6 m deep. Fig. 1 schematically shows the experimental facilities and apparatus layouts. Solitary waves were generated by a digital servo-controlled piston-type wavemaker at one end of the wave flume following the procedure suggested by Goring (1978). The other end of the wave tank had a slope to absorb and dissipate the wave energy. Solitary waves with three wave-height-to-water-depth ratios (H/h), namely 0.50, 0.45 and 0.40, were generated at a constant water depth (h) of 10.6 cm. For simplicity, only the wave condition of $H/h = 0.45$ is used in the detailed comparisons with numerical calculations. A brief description of the variations of TKE under various wave conditions is given in Section 3.2. An idealized permeable breakwater (i.e., aspect ratio $a/b = 2.0$) was mounted on the bottom of the flume with constant dimensions of 13 cm in length (a) and 6.5 cm in height (b). The breakwater consisted of uniform glass spheres with a constant diameter of 1.50 cm with those glass beads arranged in a non-staggered pattern, yielding a porosity value of 0.52. The origin of the coordinate system $(x, z) = (0, 0)$ is defined at the intersection of the seafloor and the weather side of the breakwater.

Velocity fields in the vicinity of the permeable breakwater were measured by a PIV system. A 12-bit digital CCD camera with a resolution of 1600 × 1200 pixels was used to capture instantaneous particle images. The frame rate was 20 frames per second (fps), yielding a temporal resolution of 10 phases per second. Four PIV fields of view (FOVs) were measured in order to form a continuous flow field around the porous medium. The size of each FOV was $186.04 \times 139.53\ \text{mm}^2$. The light source used to illuminate the measured section was a dual-head Nd:YAG pulsed laser system with a maximum energy output of 120 mJ per pulse, a wavelength of 532 nm and a repetition rate of 20 Hz. To avoid the wall effect, a vertical light sheet with a thickness of around 1 mm was placed a distance away from the sidewall. In the lateral direction, the measurement section sliced on the quarter of a sphere to avoid the laser beam reflection from the glass-made bead. Tiny buoyant hollow spherical glass particles with a mean diameter of 10 μm and a specific gravity of 1.05 g/cm^3 were used as seeding/tracing particles.

The time history of the surface wave profiles was measured by two capacitance-type wave gauges with a sampling rate of 50 Hz located in front of ($x = -1.8$ m, WG_1) and behind ($x = +1.8$ m, WG_2) the breakwater. The first one was chosen as the reference gauge, which means that time $t = 0$ s is defined as the time when the wave crest arrives at the first wave gauge. In addition, the experiments for each FOV were repeated up to 30 times to obtain mean quantities using the ensemble-averaged method.

2.1.2. Data analysis

The velocity fields were quantified by cross-correlation analysis with an interrogation window of 24 × 24 pixels and a 50% overlap using a zero-padding mask and Gaussian peak-finding algorithms (Raffel et al., 1998) to improve the efficacy of calculation. In addition, certain criteria were set to retain the calculated velocity vectors (Adrian, 1991) and a local median filter was employed to remove spurious vectors (Raffel et al., 1998). Based on the resolution of the PIV camera, the size of the FOV and interrogation window, the spatial resolution of the PIV system was found to be around 1.4 mm. The spatial free surface motion from the raw PIV images was detected automatically using an integrated image processing method. A median filter was first used to filter out noise from the seeding particles. The water surface was then detected with the method proposed by Canny (1986). Using the image processing technique, the instantaneous free surface motions as well as its mean quantities were obtained. The free surface data from two FOVs were then combined to form a large region.

Since both horizontal and vertical velocities were measured using the PIV system, the TKE can be estimated as $k = 1/2 < u'u' + w'w' >_N$, where < > represent the ensemble average, N is the number of repeated experiments ($N = 30$ in the present study), and u' and w' respectively