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Numerical simulation of three-dimensional breaking waves on a gravel slope using a two-phase flow Navier–Stokes model

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ABSTRACT

Wave breaking is mainly a three-dimensional flow problem characterized by wave energy dissipation due to turbulence. The understanding of the wave breaking mechanism on a beach is essential in studying coastal processes. The complexity of the wave-induced turbulence flow is also increased by the presence of a two-phase flow, which introduces buoyancy effects. In this work a set of numerical experiments is carried out on wave breaking on a gravel slope. The influence of a one-phase and two-phase flow and the permeability effect of the beach are investigated numerically by means of a Navier–Stokes model known as IH-3VOF, which considers the volume-averaged Reynolds-averaged Navier–Stokes (VARANS) equations (del Jesus, 2011 [3]) to characterize the flow within the porous media. The accuracy of the VARANS equations is demonstrated by means of comparisons with laboratory data. The results are found to be within a 2% error in terms of wave height prior to the broken wave, and up to a 10% error after then, and in the order of 0.20 s in the time domain for the worst case. A further analysis of wave evolution on a permeable beach with alongshore variation of porosity is studied. Three-dimensional wave breaking and post-breaking wave transformations alongshore are analysed according to porosity values.

1. Introduction

Wave breaking is mainly a three-dimensional flow problem characterized by wave energy dissipation due to turbulence. The understanding of the wave breaking mechanism on a beach is essential in studying coastal processes. The complexity of the wave-induced turbulence flow is also increased by the presence of a two-phase flow, which introduces buoyancy effects. In recent years, great effort has been made in improving numerical models to study wave dynamics in the surf zone by the use of Navier–Stokes (NS) models focused on the wave breaking process on impermeable slopes. However, this approach still shows discrepancies in the prediction of the breaking point and the broken wave evolution, perhaps because most of the approaches have been carried out using a two-dimensional single-phase set of equations. These studies are applicable to sandy beaches, since the velocity magnitude within the sand is at least an order of magnitude smaller than above it. In a gravel beach, permeability and the grain size could be large enough to affect the wave motion above the beach but the effects of bottom permeability on wave breaking have not been explored thoroughly. Although some attempts have been made in the past, such as by Lara et al. [1], to study wave breaking evolution on gravel beaches, there still are many features to be researched. Among other existing factors, wave breaking and porous media flow appear to be the most important drivers in this problem.

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Although the use of laboratory experiments can be an alternative, the role of scaling factors for dissipation mechanisms due to wave breaking, turbulence and generation of eddies in the fluid region, as well as turbulence and friction within the porous material, are not well established in the physical tests and of great importance in the present case. The use of numerical models based on the two-phase flow NS models appears as an alternative to experimental techniques as the number of simplifying assumptions present in the equations is lower than in other approaches. Nonlinear wave transformation processes are implicitly solved by the equations and wave breaking does not have to be triggered as in the nonlinear shallow water models or Boussinesq models. However, one of the most important features of NS models is the ability to solve the flow within porous media by means of the volume-averaged Reynolds-averaged Navier–Stokes (VARANS) equations, first introduced by Sakakiyama et al. [2] and recently modified by del Jesus [3]. Volume averaging allows considering the porous medium as a continuous medium, characterized by macroscopic properties of the medium only. The use of the VARANS equations provides very detailed solutions, both in time and in space. Moreover, the whole three-dimensional flow structure is solved and the non-hydrostatic pressures can be determined where the unsteadiness is strong. Nonlinearity is fully included, and therefore all the complex interactions among the different processes are also taken into consideration. Finally, turbulence effects can also be easily incorporated by closure models.

However, there is not a unique way to simulate porous materials using the NS equations, as another method which is based on time averaging volume-averaged equations was presented in [4]. Other published works which follow another approach include [5], in which the equations are not volume averaged, although the resistance forces due to the porous material are represented in a similar way, including the drag and inertia terms. Apart from the VARANS approach, which solves the flow in an Eulerian framework, other three-dimensional solvers are currently being used to model coastal engineering processes. One of them is SPH (smoothed particle hydrodynamics) method. For an introduction, see [6]. This method is based on solving the kinematics of given particles and their interaction with their neighbours (Lagrangian framework). Relatively new developments have led to the inclusion of porous media treatment, as presented in [7], but only for two-dimensional (2D) cases.

In this work, a set of experiments carried out on wave breaking on a gravel slope is numerically reproduced. The influence of a two-phase flow and the permeability effect of the beach are investigated numerically by means of a NS model. Numerical simulations have been carried out using a model called IH-3VOF [3]. The model solves the three-dimensional Navier–Stokes equations using a finite volume discretization. The free surface is tracked using a second-order reconstruction algorithm together with the VOF method. The model also considers porous media flow. A new set of volume-averaged Reynolds-averaged Navier–Stokes equations (VARANS) has been implemented [1], modelling the porous drag forces using the Forchheimer relationship, in which both linear and nonlinear drag forces are included. A set of volume-averaged k–ϵ turbulence balance equations is employed to calculate the turbulent kinetic energy (k) and the turbulence damping rate (ϵ), in both the clear fluid and the porous media flow region. Wave generation and absorption boundary conditions have been implemented to consider all kinds of wave characteristics, such as solitary, regular or random waves.

This manuscript is organized as follows. First, the IH-3VOF model is described, giving the mathematical formulation and explaining its numerical implementation. Numerical and experimental experiments are then described. The model is afterwards validated by comparing the results of both experiments. In the following section, a theoretical 3D case with a gradient of porosity is simulated and analysed. Finally, some conclusions are presented.

2. Description of the model

The IH-3VOF model is used, and its main features are described in this section. IH-3VOF solves the three-dimensional Navier–Stokes equations for a multiphase transient flow. It is based on the TRUCHAS model, developed at Los Alamos National Laboratory. Free surface tracking is carried out with the volume-of-fluid (VOF) technique, as developed by Rider and Kothe [8].

IH-3VOF is especially designed to simulate issues and phenomena related to coastal engineering. This is a result of some specific features that were not present in TRUCHAS model, such as a solver which handles flow in porous media with the VARANS equations, and a k–ϵ turbulence model and specific boundary conditions to generate gravity waves.

The mathematical formulation is presented first in this section, and then the numerical implementation is explained.

2.1. Mathematical formulation

The IH-3VOF model solves the three-dimensional Reynolds-averaged Navier–Stokes (RANS) equations based on the decomposition of the instantaneous velocity and pressure fields into mean and turbulent components. Reynolds stresses are closed with a k–ϵ turbulence model.

Porous (rubble mound) coastal structures or natural beaches are made of individual elements (sand, stones or armoured blocks) that usually lie randomly on the field, generating a very complex structure. It is not feasible to solve the flow field inside them directly because of the randomness of the mesh. Furthermore, the gaps would require a very fine grid, increasing the computational cost exponentially.

The proposed solution implies that the flow within the porous media is volume averaged in a control volume larger than the pore structure but smaller than the characteristic length scale of the flow. The following spatial average operator is