Computers & Fluids 111 (2015) 114–126

Contents lists available at ScienceDirect

Computers & Fluids

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

Review

The role of air modeling on the numerical investigation of coastal dynamics and wave-structure interactions

Maria Gabriella Gaeta [a,*], Alberto Lamberti [b]

[a] CIRI, University of Bologna, via Terracini 28, 40136 Bologna, Italy
[b] DICAM, University of Bologna, viale Risorgimento 2, 40134 Bologna, Italy

ARTICLE INFO

Article history:
Received 11 April 2013
Received in revised form 15 December 2014
Accepted 5 January 2015
Available online 14 January 2015

Keywords:
Two-phase model
Air compressibility
Breaking waves
Wave-induced loads

ABSTRACT

The paper presents a numerical investigation on the role of air modeling in simulations related to coastal dynamics. The implemented code, named COBRAS2, solves the Favre–Reynolds Navier–Stokes equations for two-phase flows. The $k-\epsilon$ model is adopted to define the Reynolds stress; the polytropic expression is chosen as the gas state equation to describe air compressibility; the Volume Of Fluid algorithm is implemented in order to track the interface. Simulations of dam-break wave and 1D water piston illustrate the model validity and accuracy, where air inertia and compressibility play a significant role in the reproduced dynamics. Wave breaking is analyzed in comparison with experimental data in order to focus on the influence of air flow in the wave propagation. Finally, air entrapment and compressibility are investigated during the wave impact on deck and on vertical wall and the opportunity to solve the implemented two-phase equations is discussed together with the aim to obtain accurate estimation of wave-induced loads.

Contents

1. Introduction

Oceans and coastal regions are characterized by two-fluid dynamics, referring primarily to air and water interactions at the free-surface with the development of bubble spray and air pocket/plume entrainment in water. In general, these processes occur as a result of wave propagation toward the shore or wave-structure interactions.

Fig. 1 shows a schematic representation of the main two-fluid flows that characterize the coastal environment and involve both air and water (phenomena related to atmospheric circulation,

* Corresponding author.
E-mail address: g.gaeta@unibo.it (M.G. Gaeta).

http://dx.doi.org/10.1016/j.compfluid.2015.01.001
0045-7930/

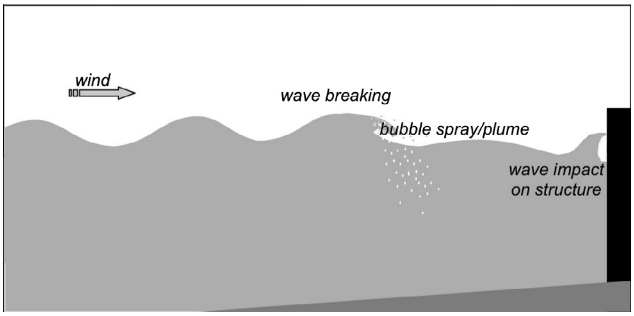

Fig. 1. A schematic representation of two-fluid flows in coastal environment.

wind generation and solid–fluid interactions are ignored). Breaking of waves is one of the multifluid coastal processes that greatly influence hydromorphodynamics, i.e., turbulence generation, energy dissipation, overtopping of maritime structures, run-up and flooding. Following common analytical and numerical approaches, wave breaking is often treated as a single-phase flow, adopting the traditional kinematic and dynamic free-surface boundary conditions.

This assumption is conventionally accepted and implemented to numerically reproduce wave propagation and transformation (Christensen [8]). Although, breaking waves are usually identified as "white waters", chaotic mixtures of air and water whose properties affect velocity and pressure field at the vicinity of the free-surface.

Indeed, according to the Galvin [17] classification, different breaker shapes commonly generate distinctive air entrainment mechanisms. Spilling waves induce air engulfment via a surface roller, with the development of bubbles close to the free-surface. In the case of plunging waves, the entrapment of air pockets occurs as an overturning jet develops and falls forward. Bubble entrainment during wave breaking plays a key role in mass and energy transport through the air–water interface (Melville [34], Führböter [16]), thus revealing how a large portion of the initial wave energy that is first stored by the air and subsequently driven into the water, is dissipated via turbulence and mass transfer.

Wave-induced loads on maritime structures significantly vary in their magnitudes and durations in relation to wave breakers and their air content. In addition to the engulfment of bubbles with typical dimensions measured in mere millimeters, the impact on a vertical wall generally develops together with the inclusion of air between the wall and wave front. Different authors (a review is reported in Plumerault et al. [39]) have classified the impulsive loads related to the breaker shape and the wave dynamics that develop due to wall proximity.

According to a recent experimental investigation by Lugni et al. [32] on vertical walls, the wave front interacts with the rigid boundary before breaking and develops a pure flip-through impact (a), or it can break as it meets the wall, thus entrapping a small (b) or a large (b′) air bubble during impact. Finally, if the wave breaks prior to wall impact, phase mixing occurs, which causes an irregular evolution of the wave front (c).

The entrapped air pocket, with dimensions near those of the wave height, creates a cushioning effect as water approaches the structure (Peregrine et al. [38]) and air compressibility induces a significant reduction in the impact pressure. However, if the air bubble sizes are sufficiently large, the enclosed bubble could extend the pressure peak duration.

In general, the magnitude of impulsive pressures on vertical walls increases with a reduction in the air pocket size (Bagnold [2], Hattori et al. [19]) and the highest impact force is commonly observed when the plunging breaker entraps an air pocket, that prolongs the duration of the peak pressures (Wood et al. [44]).

Applied mathematics and computer architectures offer the ability to develop inexpensive and rapid numerical investigations that can provide detailed information on velocity, acceleration, pressure and turbulence. The majority of numerical investigations on coastal dynamics and wave-structure interactions are based on single-phase models (among others, Guanche et al. [18]). However, it is widely recognized that the air phase is an important feature to consider in studying these topics.

Due to large interfacial deformations, multi-fluid codes typically adopt Eulerian or Lagrangian approaches to solve the governing equations. In particular, among the multiphase Eulerian models, the Level Set (LS) method is adopted to track the interface in the two-phase incompressible Large Eddy Simulation (Lubin et al. [31], Lubin and Glockner [30]) and the inviscid incompressible (Colicchio et al. [12]) models, which were both recently implemented to investigate plunging breakers and impacting waves, respectively. The most popular Lagrangian solver adopts the Smoothed Particle Hydrodynamics (SPH) technique (Monaghan [35]) and the newly updated (cSPH) by Colagrossi and Landrini [11] to address violent wave impact.

Althogh Lubin et al. [31] demonstrated the influence of air resistance in a numerical study on wave breaking, Colagrossi et al. [10] reported on the numerical challenges and limitations of violent sloshing flow simulation by adopting both the cSPH and LS models. In particular, the absence of air compressibility leads to an overestimation of the pressure impact peaks, and the fluctuations induced by air bubble compression and expansion are not properly computed.

The aim of the present paper is to investigate the role played by compressible air modeling in the reproduction of breaking waves and their interaction with structures. The implemented solver, named COBRAS2, represents an extension of the two-dimensional vertical (2DV) single-phase COBRAS0 solver, originally developed by Cornell University (Lin and Liu [26]) and later implemented by Lara et al. [23].

The mathematical formulation and the numerical resolution of the two-phase governing equations are described in Section 2, which focuses on air compressibility treatment. Section 3 illustrates selected benchmark tests chosen to validate the model, i.e., the results of simulations of a dam-break wave and a 1D water piston are compared with the experimental observations, and the accuracy of the computed results is reported. Air–water interactions during breaking and at wave impact on a deck and a vertical wall are discussed in Section 4, in which the influence of air modeling is examined. Finally, some conclusions are provided in the last section of the paper.

2. Description of the model

2.1. Two-phase modeling

The formulation of the two-fluid equations and the most appropriate closure laws follow the multiphase flow theory by Drew and Passman [13], where the ensemble average of the exact conservation equations is applied to each considered phase.

Let $\varphi_k(x,t,\alpha)$ be the component indicator function or phase index, which, for a given realization α of the flow, takes the value of 1.0 if the phase k is present at the point x and time t, and the value of 0.0 otherwise, assuring that:

$$\sum_k \varphi_k(x,t,\alpha) = 1.0 \qquad (1)$$