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Numerical Analysis of the Internal Kinematics and Dynamics of 3-D Breaking Waves on Slopes

Benjamin Biausser and Philippe Fraunié
LSEET-LEPI, Université de Toulon et du Var, La Garde, France

Stéphan T. Grilli*
Department of Ocean Engineering, University of Rhode Island, Narragansett, Rhode Island, USA

Richard Marcer
PRINCIPIA R.D., La Ciotat, France

ABSTRACT

In this paper we describe the development and validation of a numerical model based on coupling a higher-order Boundary Element Method (BEM) solution of fully nonlinear potential flow equations to a Volume Of Fluid (VOF) solution of Euler equations, in 3 dimensions (3-D). The BEM solution is used as an initialization of the VOF/Navier-Stokes solver. Numerical simulations of breaking waves on sloping beaches for 2-D (using an earlier similar model) and 3-D flows are carried out. Finally, we simulate the breaking and post-breaking of a solitary wave over a sloping ridge in a 3-D numerical wave tank. We present an analysis of wave profiles and internal kinematics (velocity, vorticity, pressure).

INTRODUCTION

The study of breaking waves is of prime importance in many ocean and naval engineering applications, such as air-sea interactions or sediment transport, and the prediction of storm-caused damages to ocean and naval structures. Despite significant progress in recent years, our understanding of wave breaking dynamics and kinematics is still quite incomplete. Due to recent improvements in computer performances, direct Computational Fluid Dynamics (CFD) simulations of wave breaking can now be carried out and used to gain insight into these complex processes. In such problems, one numerically solves full fluid dynamics equations together with nonlinear dynamic and kinematic free-surface boundary conditions, and other boundary conditions specifying solid surfaces or open boundaries. Such computations, however, are still very demanding over large computational domains. Models based on potential flow equations—Boundary Element Methods (BEM)—are very accurate and efficient for simulating wave shoaling over arbitrary bottom topography, up to wave overturning (Grilli et al., 1994, 1996, 1997 and 2001). Such models cannot, however, simulate interface reconnections, large deformations and vorticity that occur during wave breaking. To combine the advantages of both approaches, Guignard et al. (1999) proposed using a BEM solution as an initial solution for a VOF/Navier-Stokes (or Euler) model, in which wave breaking could be fully simulated. More specifically, the VOF interface tracking method is less numerically accurate and much more computationally intensive than the Boundary Integral Equations Method (BIEM) of Grilli et al., for wave shoaling, but it allows the simulation of breaking and post-breaking stages. Further, after breaking occurs, the flow becomes rotational so that potential theory becomes invalid. This is why the coupling between the BIEM and VOF/Navier-Stokes solver is achieved. These coupled BEM/VOF computations have so far been performed in 2-D (Guignard et al., 1999). Here, we apply the same approach to 3-D problems, through coupling of the 3-D BEM model of Grilli et al. (2001) to the interface tracking, SL-VOF 3-D method of Biausser et al. (2004).

The first section briefly presents the mathematical formulation. The second section deals with the numerical methods, with details of the interface tracking SL-VOF method, and coupling with the BEM formulation for wave breaking. Then, a simple application of quasi 2-D wave breaking simulation with the 3-D BEM/SL-VOF model is presented for validation. Finally, the last section analyzes the case of a solitary wave overturning and breaking over a 3-D sloping bottom.

MATHEMATICAL FORMULATION

BEM Formulation

Equations for fully nonlinear potential flows (FNPF) with a free surface are listed below. The velocity potential $\phi(\mathbf{x}, t)$ is introduced to describe inviscid irrotational 3-D flows, in Cartesian coordinates $\mathbf{x} = (x, y, z)$, with z the vertical upward direction ($z = 0$ at the undisturbed free surface), and the fluid velocity as $\mathbf{u} = \nabla\phi$. The continuity equation in the fluid domain $\Omega(t)$ with boundary $\Gamma(t)$ reads:

$$\nabla^2\phi = 0. \qquad (1)$$

The corresponding 3-D free-space Green's function is defined as:

$$G(\mathbf{x}, \mathbf{x}_l) = \frac{1}{4\pi r} \quad \text{with } \frac{\partial G}{\partial n}(\mathbf{x}, \mathbf{x}_l) = -\frac{1}{4\pi}\frac{\mathbf{r}\cdot\mathbf{n}}{r^3} \qquad (2)$$

$r = |\mathbf{x} - \mathbf{x}_l|$ the distance from the source point $\mathbf{x}$ to the field point $\mathbf{x}_l$ (both on boundary Γ), and $\mathbf{n}$ the outward unit vector normal to

*ISOPE Member.

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KEY WORDS: Breaking ocean waves, nonlinear surface waves, Boundary Element Method, Segment Lagrangian Volume of Fluid Method, numerical wave tank, 3-D flows.