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A Hybrid LS and VOF Method for 3-D Simulation of Wave Breaking and Overtopping

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The objective of this study is to determine wave overtopping, breaking, turbulence and streaming in the surf zone and thus analyze the performance of sea defenses and predict coastal flood risk in extreme conditions. Two-dimensional (2-D) hydrodynamic models, based on structured grids, have gained prominence and been used for widespread applications in surf zone studies. Reasons for this include their relative simplicity to implement and low CPU time demand. However, the accuracy of predictions made by a 2-D model may suffer from the neglect of the additional space direction. In addition, due to the difficulties posed by structured mesh schemes, surf zone geometries must be simplified before being transformed into the modeling domain, and many irregularly shaped structures have to be removed. Nowadays, the availability of greater computing power has driven the development of hydrodynamic models using 3-D unstructured meshes. Compared with its structured counterpart, the unstructured model has several attractive advantages such as: flexible modeling of complex geometries, convenient adaptive meshing capabilities and homogeneous data structures well suited for massively parallel computer architectures (Mavriplis, Pelaez and Kandil, 2001; Venkatakrishnan, 1995). This study presents a novel, coupled VOF (VOF) / LS (LS) interface capturing scheme for the prediction of violent free-surface flows. This method will be integrated into a well validated 3-D unstructured finite volume (FV) based solver (Zhao et al., 2001, 2002) to investigate wave breaking and overtopping over a structure. Further, large-eddy simulation (LES) is employed to predict the turbulence.

INTRODUCTION

The determination of wave overtopping is crucial for analyzing the performance of sea defences and estimating coastal flood risk during extreme events. Due to the violent nature of wave breaking and overtopping, the mechanism of this phenomenon is far from being well captured in numerical simulation.

Previous investigations on the wave overtopping mainly focused on the empirical formula derived from the laboratory experiments or field observations (Saville, 1995; Owen, 1980; Owen and Steele, 1993; Franco and Franco, 1999). A lot of analytical work has also been done in this regard. However, there are strong limitations in putting these results into practice, since they rely heavily on a particular site and configuration. There is then a great interest in developing techniques which can predict wave overtopping accurately and remain applicable over a whole range of structure geometries, water levels and wave conditions. Numerical models that solve the equations of fluid flow appear to provide just such an approach.

For decades, two-dimensional (2-D) hydrodynamic models, based on structured grids, have gained prominence and been used for widespread applications in surf zone studies (Kobayashi and Wurjanto, 1989; Titov and Synolakis, 1995; Dodd, 1998; Li et al., 2004; Wang, ZY, et al., 2009; Zhang, YL, et al., 2009). Reasons for this include their relative simplicity to implement and low CPU time demand. However, the physical phenomena involved in wave overtopping, such as the interaction between wave and structure, strong turbulence and eddy vortices, are 3-D in nature. Thus, the accuracy of a 2-D model may suffer from the neglect of the additional space direction. In addition, due to the difficulties posed by structured mesh schemes, surf zone geometries must be simplified before being transformed into the modeling domain, and many irregularly shaped structures have to be removed. This impedes further applications of numerical methods to more complicated practical engineering problems.

In this study, a novel, coupled LS/VOF method based on Navier-Stokes (N-S) equations for interfacial flow simulations on 3-D unstructured tetrahedral grids is proposed. At each time step, we evolve both the LS function and the volume fraction. The LS function is evolved by solving the LS advection equation using a high-resolution characteristic-based finite volume (FV) method. The volume fraction advection is performed using a bounded compressive Normalised Variable Diagram-based (NVD) scheme (Leonard, 1991). The interface is reconstructed based on both the LS and the volume fraction information. In particular, the interface normal vector is calculated from the LS function while the intercepts are determined by enforcing mass conservation based on the volume fraction. The novelty of the method lies in that we use an analytic method for finding the intercepts on tetrahedral grids, which makes interface reconstruction efficient and conserves VOF exactly. The LS function is then reinitialized to the signed distance to the reconstructed interface. Further, the adaptive combination of high-resolution discretization schemes ensures the preservation of the sharpness and shape of the interface while retaining boundedness of the volume fraction field. Since the LS function is continuous, the interface normal vector calculation is easy and accurate compared to a classic VOF method, while tracking the volume fraction is essential for enforcing mass conservation. The method is also coupled to a well validated finite volume-based N-S incompressible flow solver. The code validation shows that our method is 2nd order and mass is conserved very accurately. In addition, the centroid and intercept data available as a by-product of the proposed interface reconstruction scheme can be directly utilized in the development of

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