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Large eddy simulation of spilling and plunging breakers

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Abstract

A Navier–Stokes solver with a free surface model is used for simulating wave breaking, undertow, and turbulence in breaking waves. The free surface model is based on the Volume of Fluid concept. Turbulence scales larger than the grid scale are simulated directly while turbulence scales smaller than the grid scale are represented by a sub-grid scale model. Two different approaches for the sub-grid scale model have been applied, which are the Smagorinsky model and a model based on a k-equation for the sub-grid scale turbulence. The waves approach the shore in shore-normal direction and break on a plane constant sloping beach. Periodic spilling and plunging breakers are simulated for 20 and 16 wave periods, respectively. The set-up, undertow, and turbulence levels are compared to experimental results. Despite the rather coarse resolution of the computational domain, satisfactory results for the wave height decay and undertow have been obtained. However, the turbulence levels are over-predicted when using the standard values of the model parameters and a complete answer to this problem has not been found. Furthermore, the evolution of vorticity over the wave period has been studied. It shows that at the initial breaking point vorticity is generated around the vertical as well as around the transverse axis. Later vorticity around the longitudinal axis (offshore–onshore direction) is generated, probably through deformation of vorticity around the other axis.

Keywords: Breaking waves; Undertow; Flow structures; Numerical models; Large eddy simulation

1. Introduction

The study of surf zone dynamics has been subject to extensive research during the last few decades. The following papers give a good introduction to the subject: Peregrine (1983), Battjes (1988), and Svendsen and Putrevu (1996). Christensen et al. (2002) give a review of the latest research of the flow structures across the surf zone, Longo et al. (2002) review the research on turbulence in the surf zone, and Elfrink and Baldock (2002) focus on the swash zone dynamics.

One of the early optical measuring techniques, LDV, has been used widely for the surf zone breaking wave investigations. Stive (1980) was among the first, if not the first, to apply the LDV technique to measure the internal flow field under periodic breaking waves. Nadaoka and Kondoh (1982) presented LDV measurements for the internal velocity field within the surf zone. Nadaoka et al. (1989) used the LDV technique to study the structures of turbulent flow field of spilling breakers in the surf zone. One of the recent comprehensive studies on turbulence transport under surf zone breaking waves using LDA technique was that of Ting and Kirby (1994, 1995, 1996). The turbulence transport was studied in detail by determining each term in the k-equation. Interesting results were reported especially on the different mechanisms between different types of breaking waves. The cross-shore sediment transport, which is associated with the correlation between the mean and turbulent flow, was found from simple reasoning to be offshore under spilling breakers but onshore under plunging breakers.

Experimental investigations of the aerated region in the upper part of breaking waves cannot use optical measuring techniques as air bubbles too often corrupt the optical signal. Therefore other techniques are employed as in Jansen (1986) and more recently Lin and Hwung (1992). They used a flow visualisation technique with the use of ultraviolet light to illuminate fluorescent tracer particles, which were fed into the air bubble region. Their photographic and video images

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revealed a well-known sequence of jet-splash motions in both plunging and spilling breakers. In Jansen's (1986) results, smooth trajectories of the particles inside the jet-splash motions suggested so-called coherent motions in the flow. In Lin and Hwung's (1992) results, the main mechanism that drives the motion in the bubble zone was found to be the vortex system that was generated from the jet-splash cycles. Vortex stretching was also found to occur due to the interaction between the jets, the vortices, and the effect of the rising buoyant bubbles. These effects are perhaps the main causes of the development of the obliquely descending eddies observed by Nadaoka et al. (1988) and Nadaoka et al. (1989). In the field experiments eddies were found to involve large amounts of air bubbles which enhanced the upwelling of sediment. Due to scale effects the amount of entrained air is relatively larger in large waves (field experiments) compared to small waves (laboratory experiments).

The most direct way to investigate the flow in the surf zone numerically is to solve the basic equations for Newtonian fluids, called the Navier–Stokes equations. In many other areas than coastal hydrodynamics, such as aerodynamics and fluid mechanics, the method has gained much attention during the last few decades evolving into a whole discipline called Computational Fluid Dynamics (CFD). The method is capable of calculating the flow in complex geometries to give very refined information about velocities, turbulence, transport properties, etc.

A highly recognised method for free surface flow is the marker and cell method, which was invented by Harlow and Welch (1965). It is based on markers that are distributed all over the fluid domain. Each marker follows the velocity field in a Lagrangian way. An example of the MAC method used for breaking waves is given in Sakai et al. (1986). A similar method to the MAC method is the surface markers method presented by Chen et al. (1991) and used for breaking waves in Christensen and Deigaard (2001). Here the markers are only situated at the surface, which reduces the computational costs and improves the accuracy.

The above methods find the position of the surface in a Lagrangian manner. Another approach that has been widely used during recent years is based on a continuity equation for a conservative quantity F that is solved in a Eulerian way. A straightforward way to solve the problem is to use a very accurate higher order convection scheme such as QUICK, used by Kawamura and Miyata (1994). In their case both the air and fluid flow were simulated around ships and submerged bodies. In Hirt and Nichols (1981) a special advection scheme was used to avoid smearing of the surface, which they called the "Volume of Fluid", also known as VOF. This method has been extensively used, modified, and improved by several researchers. The approach described in Ubbink (1997) is used in this work.

An early attempt to model flow and turbulence in the surf zone was undertaken by Lemos (1992). He applied the original VOF method invented by Hirt and Nichols (1981) together with a k–ε-model to represent the turbulence scales in the simulations. The results showed that the approach could be used for simulating surf zone turbulence, though turbulence levels were over-predicted. Lin and Liu (1998a,b) used a similar approach to Lemos (1992), but with a further developed code of Hirt and Nichols (1981) by Kothe et al. (1991). Again the k–ε-model was used for representing the turbulence scales. As in Lemos (1992), Lin and Liu (1998a,b) found that the turbulence levels at breaking were overestimated. The error was of the order of 2 to 3 times the measured quantity. In the inner zone the turbulence is in general 25% to 50% higher than measured in Ting and Kirby (1994). A similar approach as the one sketched above was used in Lin and Liu (1998b) to investigate the turbulence transport and vorticity dynamics in the surf zone under plunging breakers. Compared to the results of a spilling breaker the results for the plunging breaker case compare better with measurements with respect to the undertow. The turbulence levels are too high just after the breaking point but closer to the shoreline the turbulence levels seem to be of the same order of magnitude as in the experiments by Ting and Kirby (1995). Bradford (2000) made a comparative study of three turbulence models. All three turbulence models used the turbulent viscosity concept combined with different formulations of the k–ε model. In general the model like k–ε-model and k-model gave an average turbulence level that was twice as large as the experimental levels reported by Ting and Kirby (1994) for the spilling breaker, while the RNG-model gave slightly smaller overestimations. The turbulence levels were found to be very close to the measured ones in the case of a plunging breaker, which agreed well with the results shown in Lin and Liu (1998a). The undertow found by both Bradford (2000) and Lin and Liu (1998a) was in general too low or directed towards the shore instead of offshore in the spilling breaker, which perhaps indicates that a periodic solution had not been found yet.

Even though Lin and Liu (1998a,b) used a more advanced description of the Reynolds stresses than Bradford (2000), their formulation did not show substantial improvements over the isotropic models. The choice of the boundary conditions, grid resolution, and the model coefficients all seem to have more impact on the solution. Mayer and Madsen (2000) found that the traditional turbulence models never find a stationary level of turbulence and eddy viscosity. The problem arises due to stability problems in the k–ω model in wave driven orbital motion. In Zhao et al. (2000) a multi-scale turbulence model is set-up based on a $k-l$ model. Since the production term is still related to the strain rate the waves produce turbulence before they actual have broken. The instability reported by Mayer and Madsen (2000) was avoided, and therefore the simulated water elevations agreed well with measurements. Recently, Emarat et al. (2000) studied the mechanics of a surf zone plunging breaker. Results from 2D PIV measurements were compared against those from a numerical model based on the Navier–Stokes equations and the VOF method. Good agreement between both results was found for the comparison of the flow field