Dynamics of a collapsing breaking wave

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February 13, 2005

This is a combined experimental and computational study of solitary waves that break on-shore. Velocities and accelerations are measured by a two-camera PIV technique and compared to theoretical values from a Navier-Stokes model with a VOF method for the free surface. In particular, the dynamics of a so-called collapsing breaker is scrutinized and the closure between the breaker and the beach is found to be akin to slamming. To the knowledge of the authors, no velocity measurements for this kind of breakers are previously reported.

From images of periodic waves on a beach, Galvin (1968) discussed different types of breakers. Among these were a wave being in the transition zone between a plunger and surging breaker and named collapsing wave. The crest remains unbroken and the overturning takes place in the lower part of the front. A massive body of fluid then falls on the beach with possible trapping of a small air pocket only and no splash-up.

Solitary waves on a moderately steep slope is characterized by a parameter regime with onshore plunging, connecting the regimes with no breaking and surf during shoaling Grilli *et al.* (1997). In Jensen *et al.* (2003) the dynamics of waves on the verge of onshore plunging, on a 10.54° slope, were investigated with the PIV technique. Among other things, acceleration distributions leading to reversal of breaking in overhanging waves were reported. In the present paper another set of experiments with runup on a 7.18° slope is studied. The velocity and acceleration distribution in massive onshore plungers are measured with PIV and computed by a VOF technique Mayer *et al.* (1998*a*). This investigation is aiming at recognition of cases leading to extreme runup and onshore impact of tsunamis and swells.

The measured and computed velocity and acceleration patterns are qualitatively very different from those of non-breaking waves in Jensen *et al.* (2003) and plungers in deep water. The need for spatial and temporal in this process is challenge both in the experiments and the VOF simulations.

All experiments were performed in the wave tank at the Hydrodynamic Laboratory, Department of Mathematics, University of Oslo. The wave tank is 1 m high, 0.5 m wide and 25 m long. At one end of the tank waves were generated by a hydraulic piston attached to a vertical paddle.

A definition sketch of the wave tank and the beach is shown in figure 1. To allow for large amplitudes the experiments were carried out with an equilibrium depth (h) equal to 20 cm. In all run-up experiments a beach with an inclination of $\theta = 7.18^\circ$ is located at a distance $L = 40.39h$ from the undisturbed position of the wave maker.

The free surface is measured by an acoustic wave gauge when it travels on finite depth. Figure 2 shows a solitary wave measured by this method. The maximum wave elevation is found with very good accuracy, while the errors are larger on the slopes of the wave profile due to signal dropouts. Free surface profiles are also extracted from digital images to acquire

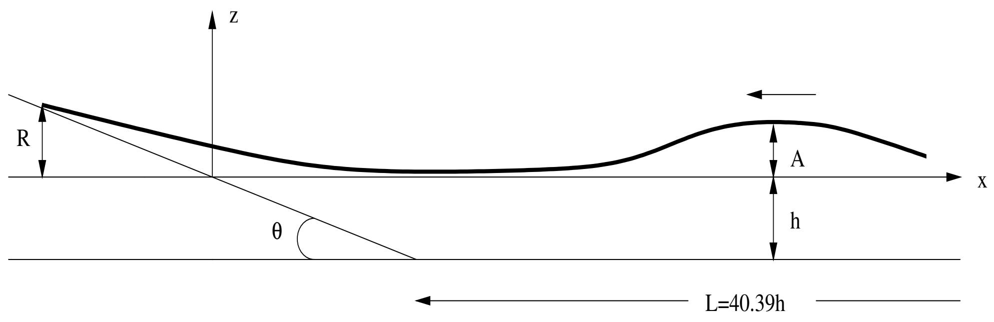

Figure 1: Definition sketch of the wave tank.

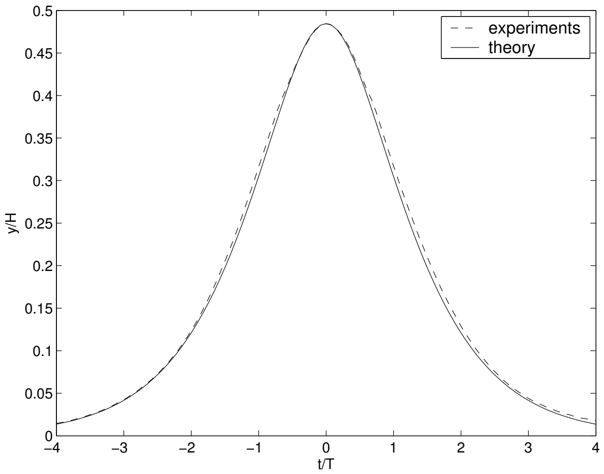

Figure 2: Incident solitary wave compared to theory (Tanaka (1986)).

the spatial distribution.

All numerical results in the present paper are computed by an incompressible Navier-Stokes solver with codename NS3. The basic spatial and temporal discretization of NS3 follows Mayer *et al.* (1998*b*), Mayer & Madsen (2000) and Kawamura *et al.* (2002), using projection and a finite volume method with cell-centered variable layout on moving general curvilinear multi-block grids using the Arbitrary Lagrangian Eulerian (ALE) approach. Numerical time integration of the momentum equation is performed to second order accuracy. By using the finite volume methodology the mass and momentum equations are discretized in a cell-wise fully conservative manner, the change in time of mass or momentum within a cell being identically reflected in the fluxes of mass and momentum, respectively, over the cell boundaries. This feature is particularly important in cases with low spatial resolution.

To describe the free surface geometry an interface capturing scheme, similar to the VOF methodology of Hirt & Nichols (1981), is applied. It uses an implicit representation of the free surface based on volume fractions, see Nielsen (2003). Above the free surface the grid is extended to ensure that the water domain is within the grid boundaries at all times during the simulation. A scalar field f (the volume fraction) is introduced, and cells with $f > 0.5$ are flagged to be fluid cells, while cells with $f < 0.5$ are taken to be void cells and passive in

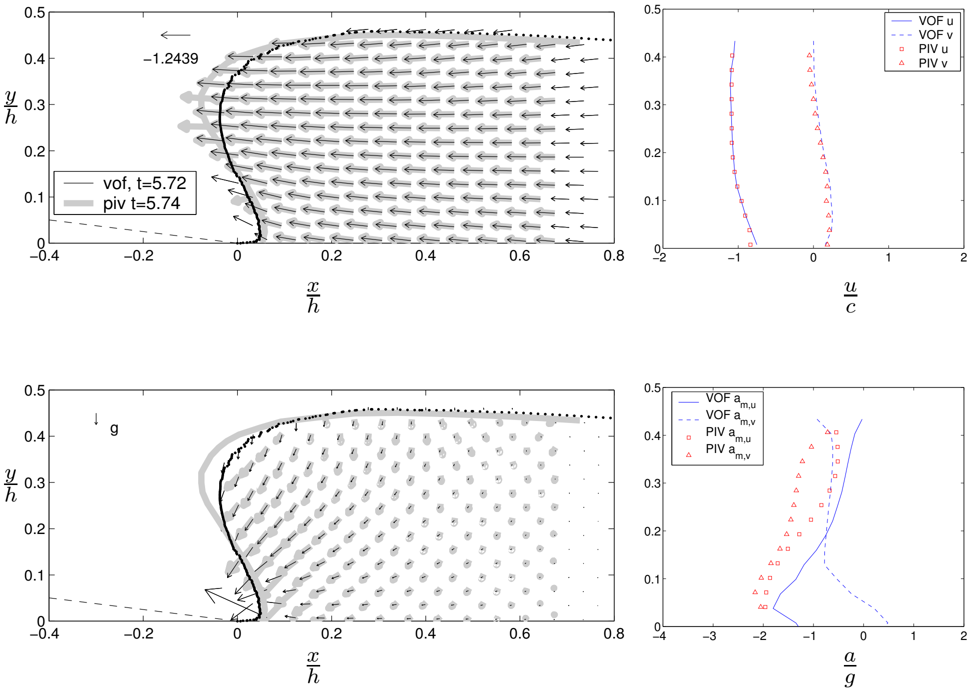

Figure 3: $a/h = 0.49$, PIV: $t = 5.74s$, gray arrows in left column, symbols for the profiles. VOF: $t = 5.72s$ black arrows and solid/dashed. From top: velocity vectorfield. Bottom: acceleration.

the solution process of the mass and momentum equations. The time dependency of the free surface geometry is described by solving a transport equation of the field quantity f,

$$\frac{\partial f}{\partial t} + (\boldsymbol{u} \cdot \boldsymbol{\nabla}) f = 0. \tag{1}$$

In order to ensure a steep gradient of f across the free surface, the special compressing transport scheme CICSAM by Ubbink (1997) is employed and extended to second order accuracy in time. All computations are carried out with variable time increments Δt, at every time step, keeping the maximum cell Courant number within the limit $U\Delta t/\Delta x < C_{cfl}$. The Courant number is $C_{cfl} = 0.25$.

For the largest wave studied, $a/h = 0.49$, PIV measurements are performed at $t = 5.74, 5.76, 5.78s$. At the first time (figure 3) the surface is markedly over-hanging and the velocity field is dominated by a strong alongshore component, but variations are apparent near the front. Computed and experimental values (VOF taken 2/100s before) show remarkably good agreement. However, there is a discrepancy in the shape of the front. The surfaces intersect the beach at the same position, but the experiment has a more pronounced protrusion at the front. At this stage there is a strong horizontal acceleration close to the beach (see bottom panel). Moreover, we observe that the accelerations in the overhanging part are also large, and directed downward. Experimental and computed accelerations have roughly similar patterns, but there are significant differences.

This appearance and development of this breaking wave is very different from a pointed plunger in finite depth. The typical finite depth plunger forms at the top of the crest and may crudely be regarded as a transition from potential to kinetic energy, manifesting itself in a thin forward jet. The head of the collapsing breaker is formed over the whole height of the incident wave and is fed with fluid from the toe of the wave as well as from the crest.

The results indicate that fluid particles are transported from, and presumably through, the onshore contact point and up the overhanging front.

Both experiments and theory points strongly towards a slamming mechanism for closure of the air gap between the breaker and the beach. A flip-through motion from the contact point is in embryo, but probably do not develop in time to fill the gap before it is closed by the bore collapse.

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