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Numerical simulation of wave breaking in shallow waters by using a SL-VOF method

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Abstract

Numerical simulations of wave breaking in shallow waters have been performed by using the finite volume fluid mechanics code "EOLE" developed by Principia R&D. To this threedimensional, curvilinear, multidomain model has been added an original Segment Lagrangien - Volume Of Fluid (SL-VOF) method, very accurate when dealing with highly non linear interfaces.

Results concerning the interface evolution, the velocity and pressure fields in the shoaling zone and in the surf zone are presented for a solitary wave normally incident on bottoms of constant slope. The results are successfully compared with those obtained by numerical models based on the Boundary Integration Element Method (BIEM).

1 Introduction

The investigation of wave breaking is of practical importance in oceanography and in coastal engineering for its contribution in the coastal circulation and sediment transport processes, and for its action on floating or submerged structures. The wave breaking simulations purpose is to deduce stresses on structures and sediment motion conditions in direct correlation with the velocity and pressure fields on the bottom, and significant wave height for shoaling and broken waves for improving the wave forcing parametrization in 2DH coastal circulation models via the radiation stresses.

Two major problems appear when simulating wave breaking : The high non-linearity of the waves near breaking and the rotational viscous two phase flow characteristic of wave breaking (two fluids of strongly different density have to be considered). Moreover, the quality of the interface definition is of major importance for the numerical process.

Numerical models with free surfaces, fast and accurate, based on BIEM describe precisely the wave shoaling [1]. If they are very convenient models for very steep waves in very shallow waters, they cannot take into account the viscous, rotational, multi-interfaced, characteritics of the flow during breaking.

The model presented here takes into account the viscous effects by solving the incompressible Navier-Stokes equations using a pseudo-compressibility method [2] and is able to modelise the wave after breaking including jet impact and splash-up, what cannot do the BIEM. The interface tracking is performed by a new mixed SL-VOF method very convenient for very steep and broken interfaces. It is applied to the case of solitary waves propagating normally incident on bottoms of constant slope and compared with those obtained by numerical models based on the BIEM.

2 The model

2.1 Balance equations and Navier-Stokes solver

The problem consists in solving the mass and momentum balance equations for two incompressible viscous fluid of different density in a two dimensional vertical flow (2DV). In a cartesian system xOy, with Oy vertical upwards, the equations are as follow:

$$\frac{\partial W}{\partial t} + \frac{\partial F}{\partial x} + \frac{\partial G}{\partial y} = R \tag{1}$$

where

$$W = \begin{bmatrix} 0 \\ \rho u \\ \rho v \end{bmatrix} F = \begin{bmatrix} \rho u \\ \rho u^2 + p + \tau_{xx} \\ \rho uv - \tau_{xy} \end{bmatrix} \tag{2}$$

$$G = \begin{bmatrix} \rho v \\ \rho uv + p + \tau_{yx} \\ \rho v^2 - \tau_{yy} \end{bmatrix} R = \begin{bmatrix} O \\ O \\ -\rho g \end{bmatrix}$$

where (u, v) are the components of the velocity field, p is the pressure field , $\tau_{ij}(i, j = x, y)$ the components of the viscous stress tensor, ρ_i $(i = 1, 2)$ respectively densities of water and air and g the gravitational acceleration. Equations are solved thanks to a pseudo-compressibility method which consists in rewritting the system (1) by introducing a pseudo-compressibility variable and the pseudo-time variable [2].

2.2 Interface treatment

The interface and its temporal evolution are solved by using an original method based on the well known concept VOF [3]. The interface is modelled in each cell thanks to a discrete function C which value for each cell is the fraction of the cell occupied by the denser fluid (VOF concept). The normal $\vec{n}$ to the interface in each cell is defined by the direction of $-\vec{grad}(C)$, and the interface in this cell by a segment normal to $\vec{n}$ and which position is evaluated so that the fraction of the cell delimited on the opposite side of the normal is equal to the value of C in this cell (Calcul d'Interface Afine par Morceau, CIAM) [4]. The velocity at extremities of each segment is deduced from the general velocity field thanks to a bilinear interpolation. The extrema of the segment are then advected (Lagrangian concept). At least, the new position of the segment after advection allows to calculate new values of C.

3 Results

The propagation of a solitary wave has been studied. This type of wave is very convenient for numerical simulation as the boundary condition is very simple : Nul velocity far from the crest. Moreover the solitary wave model have been studied by many authors [1] [5] [6] and give us a very strong database for comparisons. Moreover, such a model of wave is quite appropriate in the nearshore zone for long waves shoaling on gentle slopes [7] [5] .The initial pressure and velocity fields are those of an exact solitary wave on a flat bottom. The case of a solitary wave of $0.5m$ height first propagating over on horizontal bottom of constant depth $1m$ and then over a constant sloping bottom of $\frac{1}{15}$ slope is presented.

3.1 Interface shape evolution

The interface shape changes during the wave propagation towards the beach (shoaling phenomenon). The wave height evolution is a very important data taking part into the radiation stresses (RS) calculation at each point of the nearshore fields. The RS are the forcing terms provided by waves taken into account in the classical 2DH coastal circulation models. Figure 2 shows the evolution of the interface shape during shoaling (respectively at $t = 0s; 3.72s; 3.82s; 5.01s$), figure 3 represents its evolution during breaking (respectively at $t = 5.01s; 5.18s; 5.30s; 5.44s, 5.56s$), the breaking instant is here defined as the moment when the interface has a vertical tangent for the first time. The breaking abscissa is the horizontal position of the crest at this instant.

Results concerning the wave height during shoaling, its height at the breaking point, and the breaking abcissa are compared with results obtained with BIEM on the same slope and water depth but for various wave height [1].

Figure 4 shows similar evolutions of the wave height during shoaling with a difference less than $7 percent$. The values of X_b obtained with BIEM for various initial wave heights and those obtained with the method presented here are reported on figures 5 and 6.

In all cases, a very good agreement between the two methods is observed.

3.2 Pressure and velocity at the bottom

Calculations of pressure and velocity fields at the fluid-solid interface are of major interest for the evaluation of loads on structures, or for the parametrization of the nearshore sediment transport. Figures 7 and 8 show respectively the evolution of the intensity of the velocity and of the total pressure in the vicinity of the bottom at two different positions, the first one before X_b at $x = 29.0m$, the second one after X_b at $x = 32.9m$. The results dwell upon a very fast evolution of the fields in this zone which may have strong effects on structures and bottom shape evolution.

4 Conclusion

Results of the present model have been presented here, with particular attention to those concerning the interface shape evolution and the velocity and pressure fields in the shoaling and surf zones, for solitary waves normally incident on beaches of given constant slope.

The comparison with results obtained by BIEM shows the capability of such a model to describe wave evolution up to breaking. The weak differences observed with the BIEM method before breaking are due to the intrinsec hypothesis of each model and to the numerical precision of our model which was found to be very weak (energy loss of the entire computation less than one percent). As it takes into account the viscous effects, our model allows a better representation of the physical phenomena near the breaking point where viscous effects must be considered.

Academic examples were presented here but applications to more complex bottom topographies, including artificial structures, can be performed. Further developpements of the method for periodic waves are scheduled.

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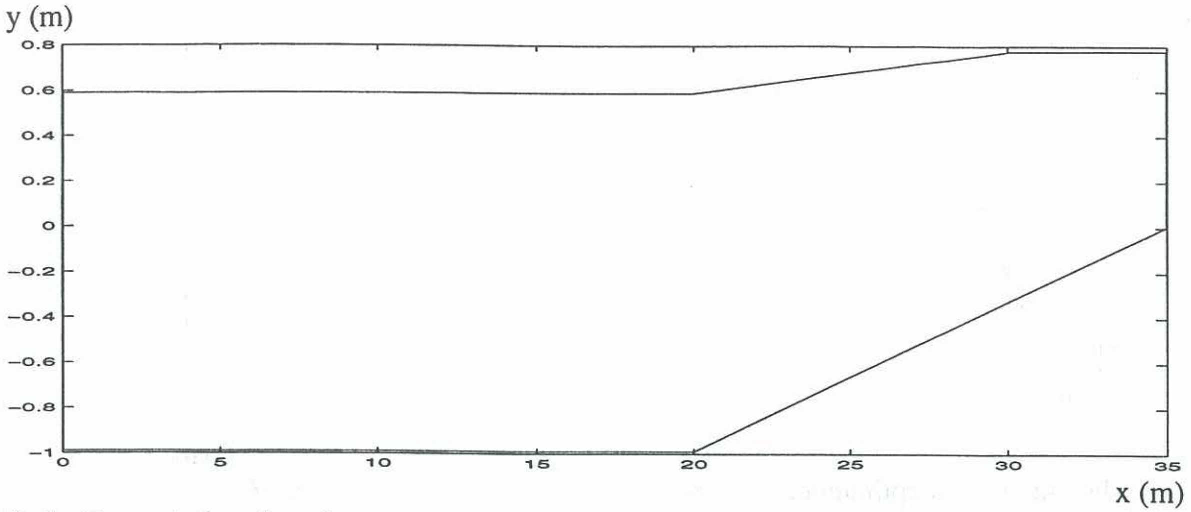

fig1 : Computation domain

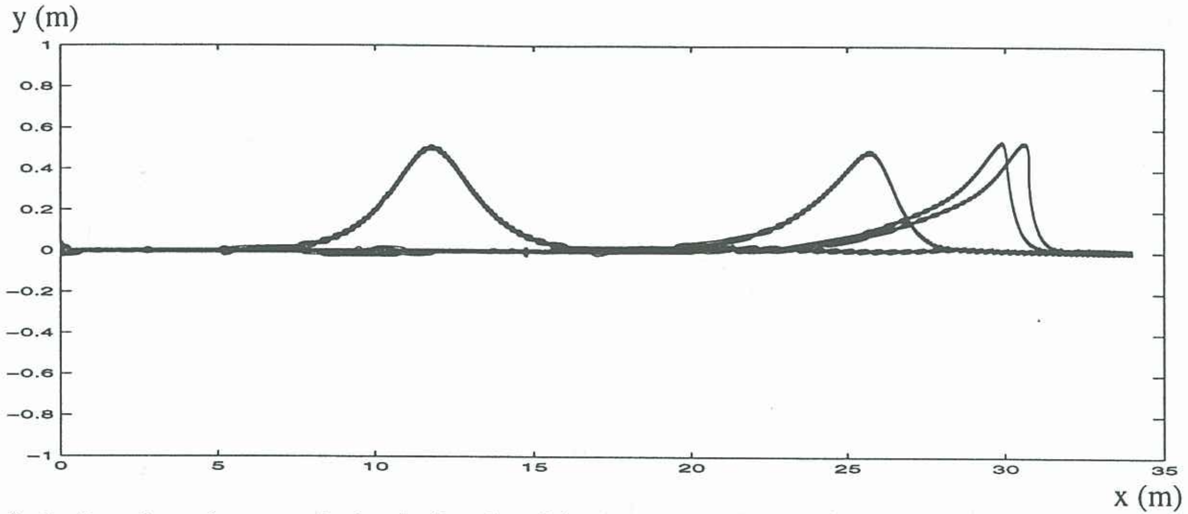

fig2 : Interface shape evolution before breaking

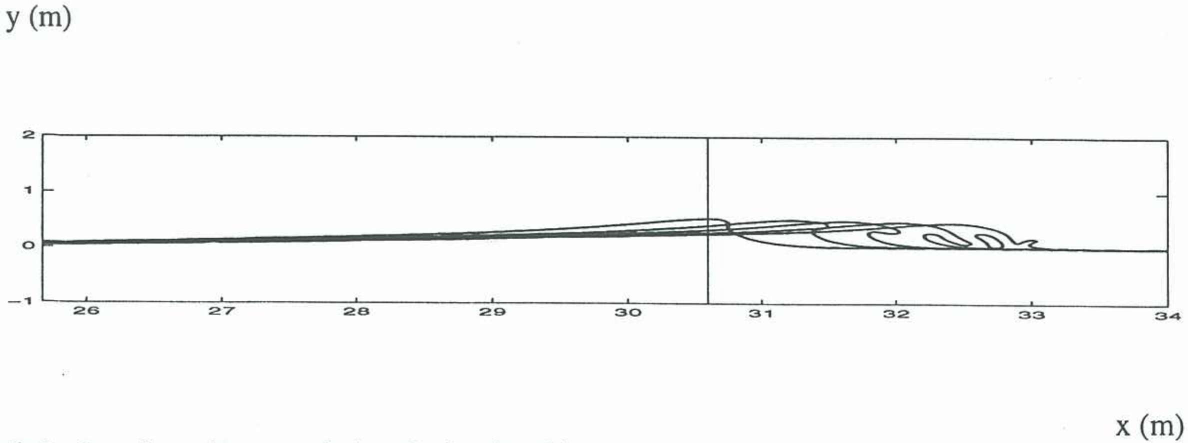

fig3 : Interface shape evolution during breaking

Crest position at the breaking point

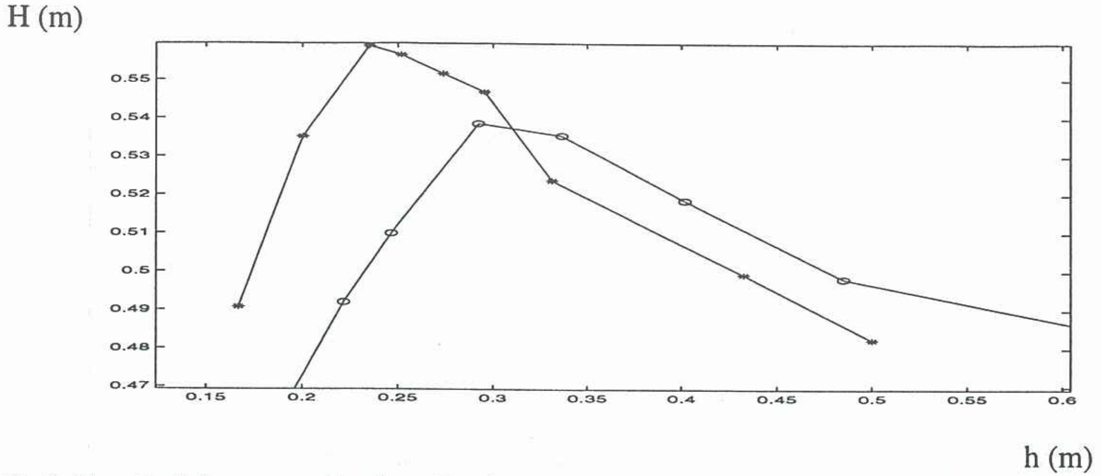

fig4 :Crest height versus depth under the crest:

* :BIEM
\+ :VOF method

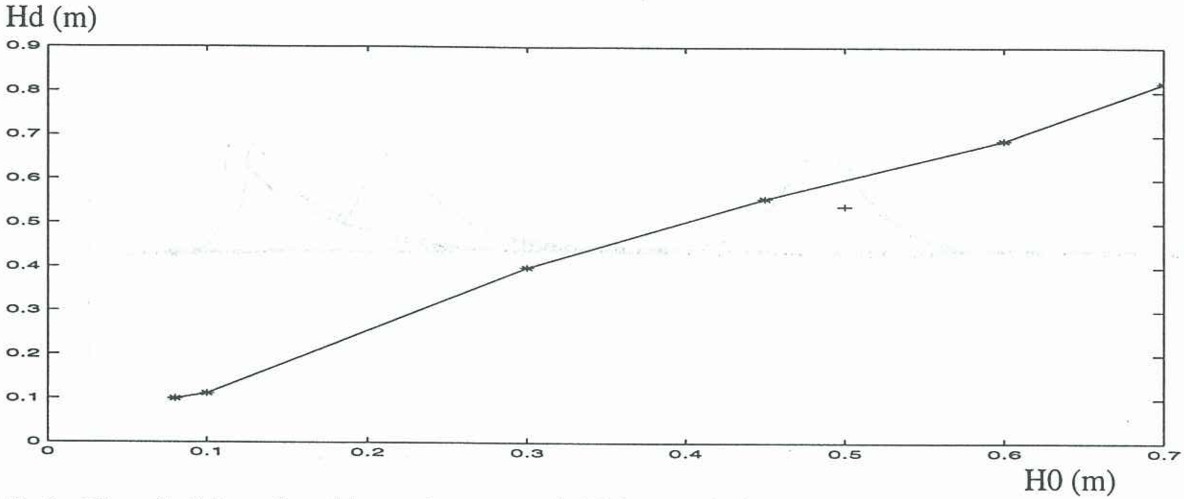

fig5 : Wave height at breaking point versus initial wave height

* :BIEM
\+ :VOF method

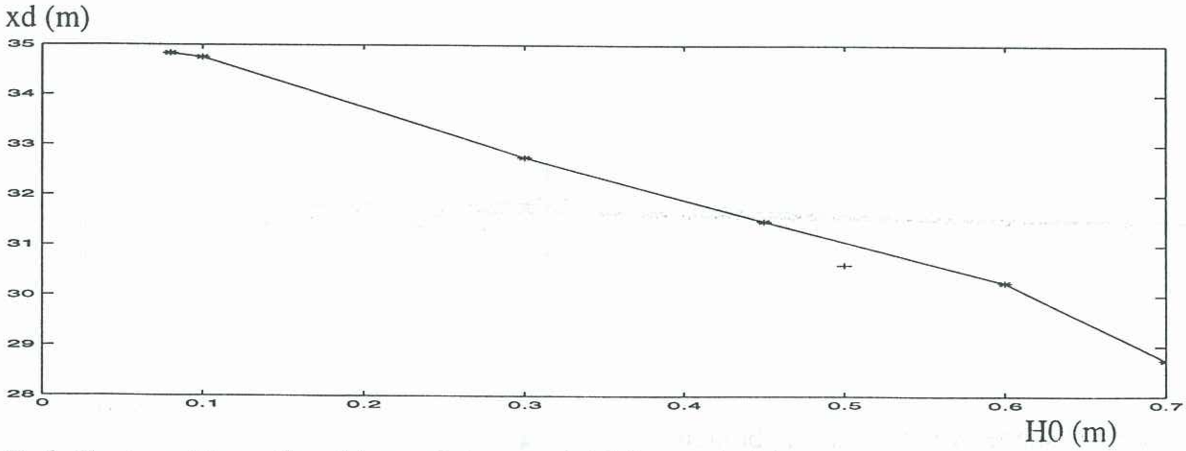

fig6 :Crest position at breaking point versus initial wave height:

* : BIEM
\+ : VOF method

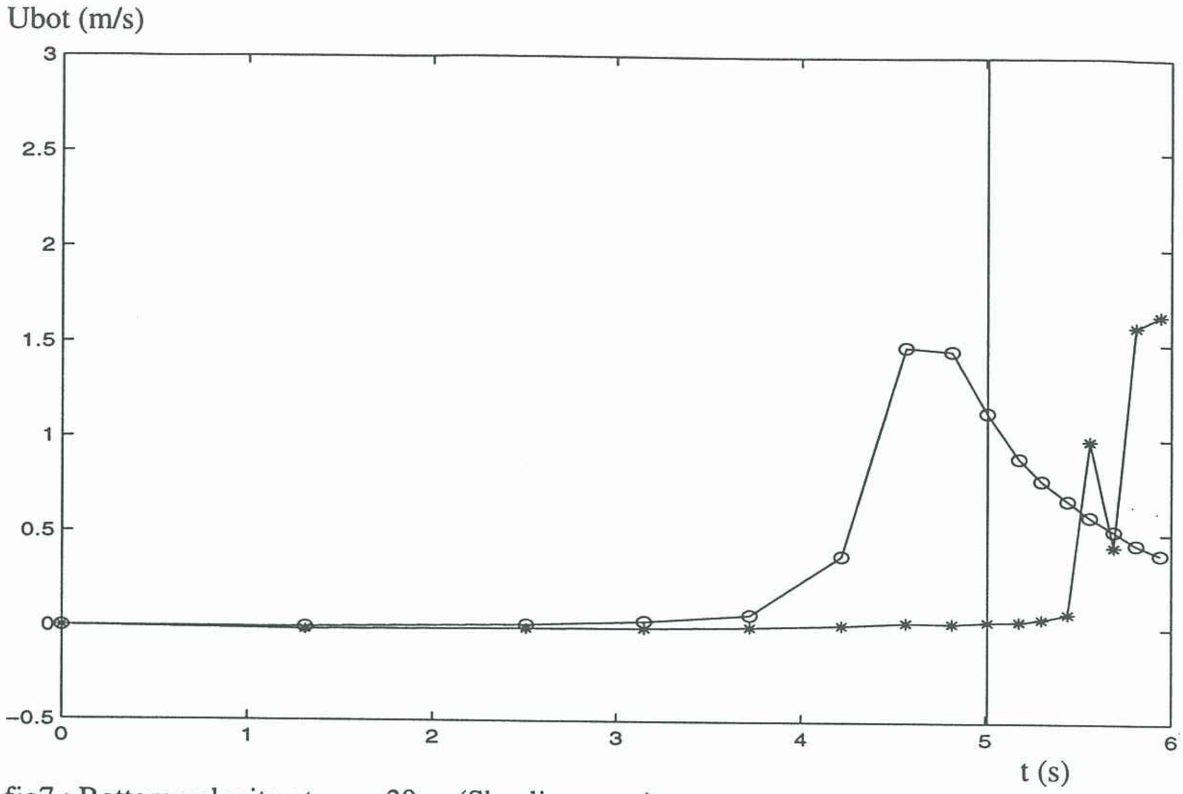

fig7 : Bottom velocity at : x = 29 m (Shoaling zone) : ——
x = 31,7 m (Surf zone) : *

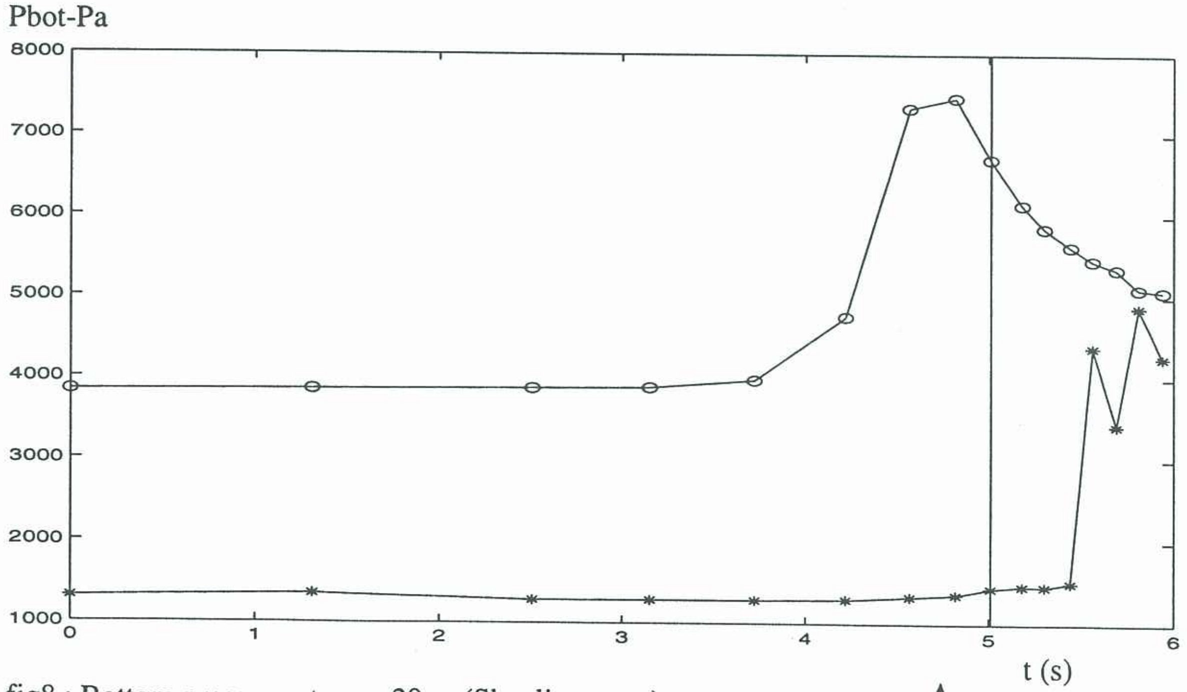

fig8 : Bottom pressure at : x = 29 m (Shoaling zone) : ——
x = 31,7 m (Surf zone) : *

crest position at the breaking point