WATER ENTRY AND EXIT OF HORIZONTAL CYLINDER IN FREE SURFACE FLOW

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ABSTRACT. This paper describes two-dimensional numerical simulations of the water entry and exit of horizontal circular cylinder at constant velocity. The deformation of free surface is described by Navier-Stokes (NS) equations of incompressible and viscous fluid with additional transport equation of the volume-of-fluid (VOF). The motion of the cylinder is modeled by the associated momentum source term implemented in the PHOENICS (Parabolic Hyperbolic Or Elliptic Numerical Integration Code Series) code. The domain is discretized by a fixed Cartesian grid using a finite volume method and the cylinder is represented and cut cell method. The simulated results are compared with the numerical results of Lin (2007). This comparison shows good agreement in terms of free surface evolution for water exit and sinking. However, for water entry, the jet flow simulated by Lin is not reproduced. The free surface deformation around the cylinder in downward direction is accurately predicted.

INTRODUCTION

Several practical applications in marine hydrodynamics require the accurate prediction of nonlinear wave loads in the vicinity of a moving body. Such loads induced by water impact can give rise of structural failure due to fatigue stressing of the offshore structure joints (Seddon et al., 2006). In the case of violent motion, several mechanism may appears including the breaking of the free surface profile, the flow separation, an open air cavity which is then closed following different mechanism depending on the Froude number (Greenhow, 1988 and Moyo et al., 2000). In addition, the compressibility of water and the elasticity of the body affect the wave loads on the marine structure. The free surface breaking can not be predicted using inviscid fluid assumption (Tyvand et al., 1995). Such model can only simulate the post breaking phase. The Navier-Stokes transport equations are needed for the prediction of free surface breaking (Clarke et al., 2008).

When simulations include a highly distorted free surface, a fixed Cartesian grid is very suitable. Then the free surface is not aligned with the grid (Lin, 2007). Another alternative is to use a moving body fitted grid. This method was used by Zhang to simulate the solitary waves generated by a submerged semicircular body moving with uniform velocity (Zhang et al., 1996). However, for long numerical simulation with violent boundary motion, the re-meshing is distorted. To overcome this limitation, a fixed Cartesian grid can be used in which the moving boundary can be accounted in different ways: the **immersed boundary method**, the **fictitious domain** method and the **cut cell** method. The first two methods treated the boundaries of the object as a special region in a single phase. So, the whole domain is filled with liquid, and **body forces** (in cells containing the moving object boundaries) account for the presence of the moving objects (Uzgoren et al., 2007). In the **cut cell** method, the object is solid and the sharp object boundary is cutting through the grid cells. For moving object, the boundary "sweeps" through a fixed Eulerian mesh over a timestep (Murman et al., 2003 and Tucker, 2000). A conservative scheme is formulated for the swept cells by approximating the flux through all of the moving cell faces.

In this study we present, a two dimensional free surface model based on Navier-Stokes equations. The free surface deformation induced by the horizontal circular cylinder is described by a convective transport equation. Numerical simulation is realized by the Navier-stokes solver PHOENICS in which the cut cell method is used to capture the geometry of the body. The moving cylinder is treated as a momentum source term. The calculations are conducted for three cases: the first one is the water exit of the cylinder. In this case, the free surface of water is computed until the cylinder bring out. The sinking of the submerged cylinder is simulated in the second case. In the third case, the water impact and entry of the cylinder is investigated. All three calculations are made with constant velocity and initially calm water.

GOVERNING EQUATIONS AND INITIAL AND BOUNDARY CONDITIONS

Transport Equations. The numerical model is based on the Navier–Stokes equations that describe the flow of an incompressible viscous fluid. In two-dimensional flow, the mass conservation equation is written as:

$$\frac{\partial u}{\partial x}+\frac{\partial w}{\partial z}=0$$

(1)

where, u and w the velocity components respectively in x and z directions.
In viscous flows, the momentum transport equations in the horizontal and vertical directions can be written respectively:

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho}\frac{\partial P}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

(2)

$$\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+w\frac{\partial w}{\partial z}=-g-\frac{1}{\rho}\frac{\partial P}{\partial z}+\nu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

(3)

where P is the pressure, ν the kinematic viscosity, ρ fluid density and g the gravitational acceleration.

The volume of fluid (VOF) method is adopted to describe the free surface evolution induced by the moving body. This free surface model is a surface capturing method and is well applicable for breaking waves and jet break-up. The free surface evolution is described by an additional transport equation in terms of VOF variable which describe the volume fraction of fluid in each cell of the computation domain:

$$\frac{\partial F}{\partial t}+\frac{\partial}{\partial x}(F\ u)+\frac{\partial}{\partial z}(F\ w)=0 \qquad \textbf{(4)}$$

A cell with an F = 0 refers to en empty cell, a cell with 0 < F < 1 is a surface cell and a cell with F = 1 is a water full cell.

The free surface flow is considered as mixture flow involving water phase and air phase. We assume that the sliding between the two phases is negligible and that there is no mass exchange across the interface. Hence, the velocity field at the free surface is continued.
The fluid properties in a cell are dependent on the volume fractions of the fluids within it. The free surface occurs at cells that have volume fractions of one half for each of the two adjacent fluids.

Initial and boundary conditions: To solve the above transport equations, initial and boundaries conditions are required. The initial condition considered is a still water. The free-surface boundary conditions consist of kinematics and dynamic boundary conditions. The kinematics free surface boundary condition states that the fluid particles of the free surface always stay on the free surface at any time. The dynamic free surface boundary condition requires that, along the free surface boundary, the normal stress is set equal to the atmospheric pressure and the tangential stress is zero. The no-slip boundary condition is imposed on the cylinder inside the domain. For the moving boundary (the cylinder), the velocity is set to the prescribed velocity: w = V with V is the velocity entry or exit. This condition is implemented in the PHOENICS code by adding a momentum source term for cells occupied by the cylinder at each time step. At the other three boundaries, symmetric conditions are imposed.

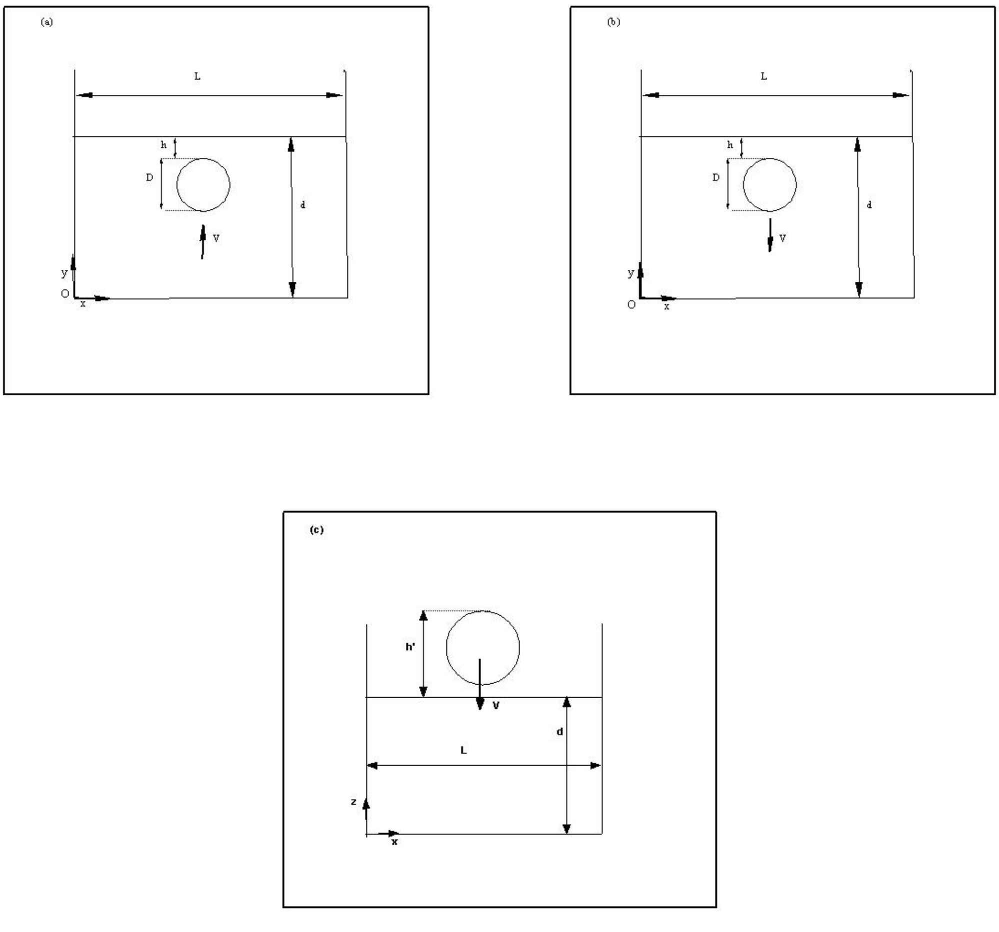

Figure 1. Definition sketch of the moving horizontal cylinder
a) water exit b) water sinking c) water entry

NUMERICAL RESULTS AND DISCUSSION

Problem description The described model is validated for three cases: water exit, water sinking and water entry of horizontal circular cylinder with forced constant velocity through initially calm water (figure 1).

In these three cases, the water depth is chosen to be d = 20 m; the horizontal cylinder has a radius R = D/2 = 1.0 m; the distance between the nearest point of the cylinder and the still water level is h = 0.25 m; the gravitational acceleration is g = 1.0 m s^{-2}; the horizontal and vertical lengths of the computational domain are respectively L = 40 m and 24 m. In the case of water exit, the horizontal cylinder moved upward with constant velocity V = 0.39 m/s. However, in the case of water sinking, the water moved downward V = -0.39 m/s. These parameters are the same used in numerical results by Lin (2007). The computational domain is discretized into 220x156 in the case of water exit and 220x276 in the case of water sinking with fine grid used around the horizontal cylinder. For water impact and entry, the 220x266 grids is used respectively in horizontal and vertical directions. For these three cases, the time size is $\Delta t = 5.00\ 10^{-3}$ s.

Water exit of a horizontal cylinder The free surface profiles induced by the upward motion of the cylinder (water exit) are shown in figure 2. The freely rising of a cylinder to a free surface may be thought of as a non-deformable bubble. The free surface profile have vertical plane of symmetry crossing the center of the cylinder. Numerical simulations show that the velocity and the pressure fields also present the same plane of symmetry. The computational domain can be reduced to the half. At t = 0.0, the cylinder is at rest and the free surface is horizontal (Figure 2-a). From t = 0.64 s to t = 2.56 s (Figures 2-b to 2-e), the free surface rise up near the cylinder. The free surface far from the cylinder is not influenced by the moving cylinder and it's not perturbed. At t = 3.20 s, the free surface break down due to the development of negative pressure in the upper part of the wetted cylinder (Figure 2-f). At t = 6.41 s, the cylinder is located just above the free surface (Figure 2-g). At t = 9.61 s, the cylinder is completely detached from the free surface (Figure 2-h). The comparison between the present results and the numerical results of Lin (2007) show that nearly perfect agreements are obtained.

Sinking of a submerged cylinder The free surface profile induced by the downward motion of the cylinder (water sinking) is shown in Figure 3. The initial condition is exactly the same as the water exit problem except the body is sinking downward (V = - 0.39 m/s). Numerical results show that the flow variables have a vertical plane of symmetry. At t = 1.28 s, the free surface around the cylinder is deformed in downward direction (Figure 3-b). As the depth of the submerged cylinder increase, this deformation is propagated to all computational domain with free surface elevation above the cylinder (Figure 2-c). At t = 6.41 s, the free surface tend to return to the initial level (Figure 3-d). Good agreement is obtained between the present model and Lin model (2007).

Water impact and entry of a cylinder To simulate the free surface deformation induced by the impact of horizontal cylinder, Lin (2007) considers the case of the stronger impact: V = - 1.0 m/s; The distance between the highest point of the cylinder and the still water depth is h' = 1.25 m (the cylinder is above the still water surface). The same initial condition was adopted in the following presented numerical results. The simulation free surface profiles are shown in Figure 4. During the initial impact of the cylinder on the free surface, the water has been push up following the cylinder surface (Figure 3-c). As the body moves further downward, numerical simulation of Lin show that jets are formed (Figure 3-d) that plunge to two sides of water surface (Figure 3-f). The jet flow is not simulated by the present model. At t = 2.50 s, a large amount of water is pulled downward (Figure 3-g). At t = 3.75 s, the cylinder is completely submerged in water and a large surface depression persists (Figure 3-h). At these two latest times the free surface profiles is accurately predicted by the present model.

CONCLUSION

For numerical simulation of a moving horizontal cylinder in a free surface flow, the cut cell technique in a fixed-grid system is used. The prescribed motion is modeled by a momentum source term in the vertical direction. This method can be generalized for complex body motions and other object shapes. Compared to numerical results of Lin [2007], the present model chows good agreement for water exit and sinking. The jet flow predicted by Lin, in the case of water entry, is not predicted by the present model. The evolution of the free surface after the jet formation is well reproduced.

This model is based on a single-phase fluid model and thus has limitation of treating air entrainment processes near free surfaces. The multiple-phase model has a better potential of treating air currents during a moving body interaction with free surfaces. After validation of the moving body in free surface flow, this model will be used for linear and nonlinear wave generation using prescribed object displacement.

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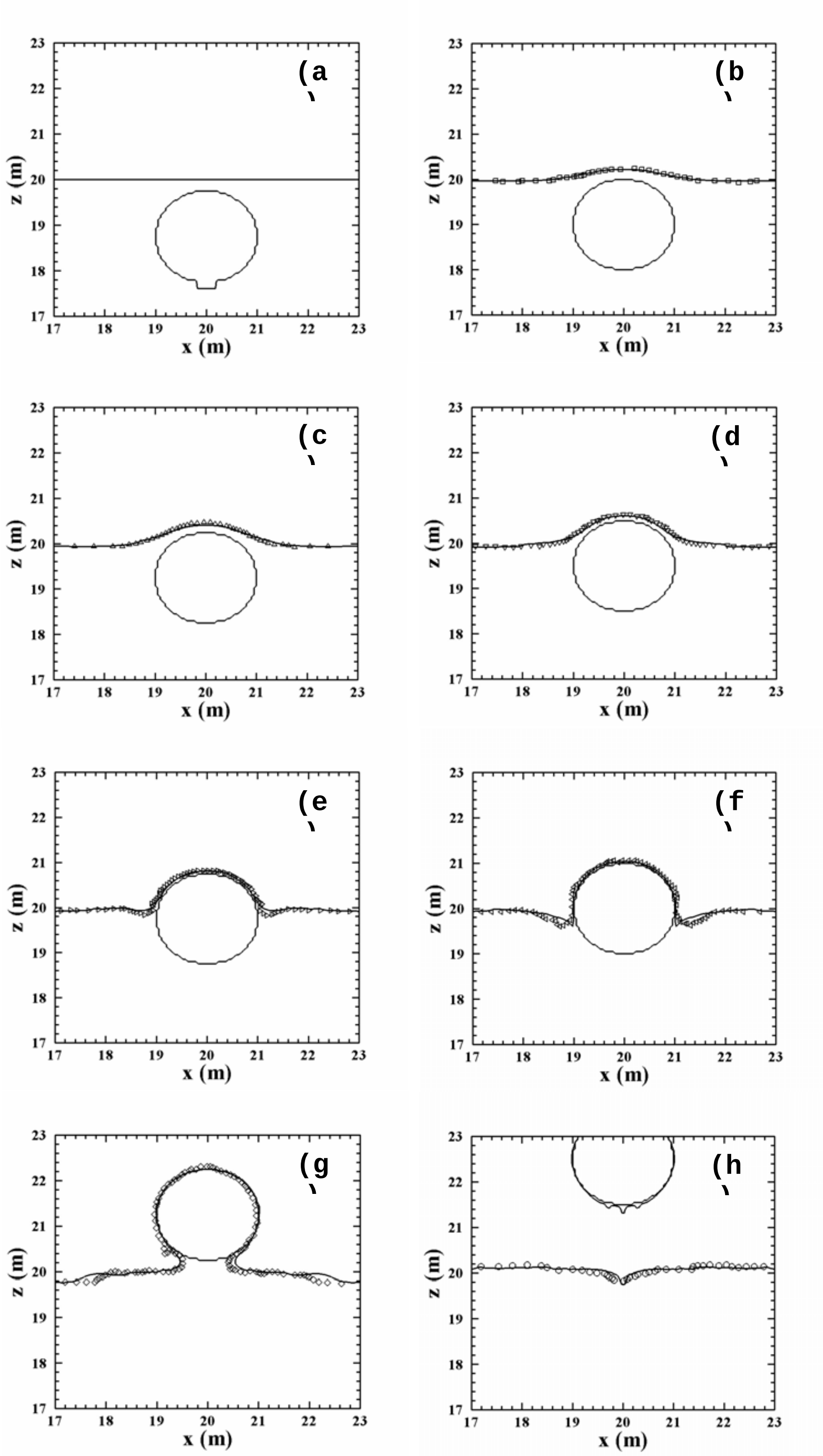

Figure 2. Water exit of horizontal cylinder. The simulated free surface profiles in the vicinity of the cylinder (—— solid line) compared to Lin (2007) numerical results (symbols); a) t = 0.00 s; b) t = 0.64 s; c) t = **1.28 s; d) t = 1.92 s; e) t = 2.56 s; f) t = 3.20 s; g) t = 6.41 s; h) t = 9.61 s.**

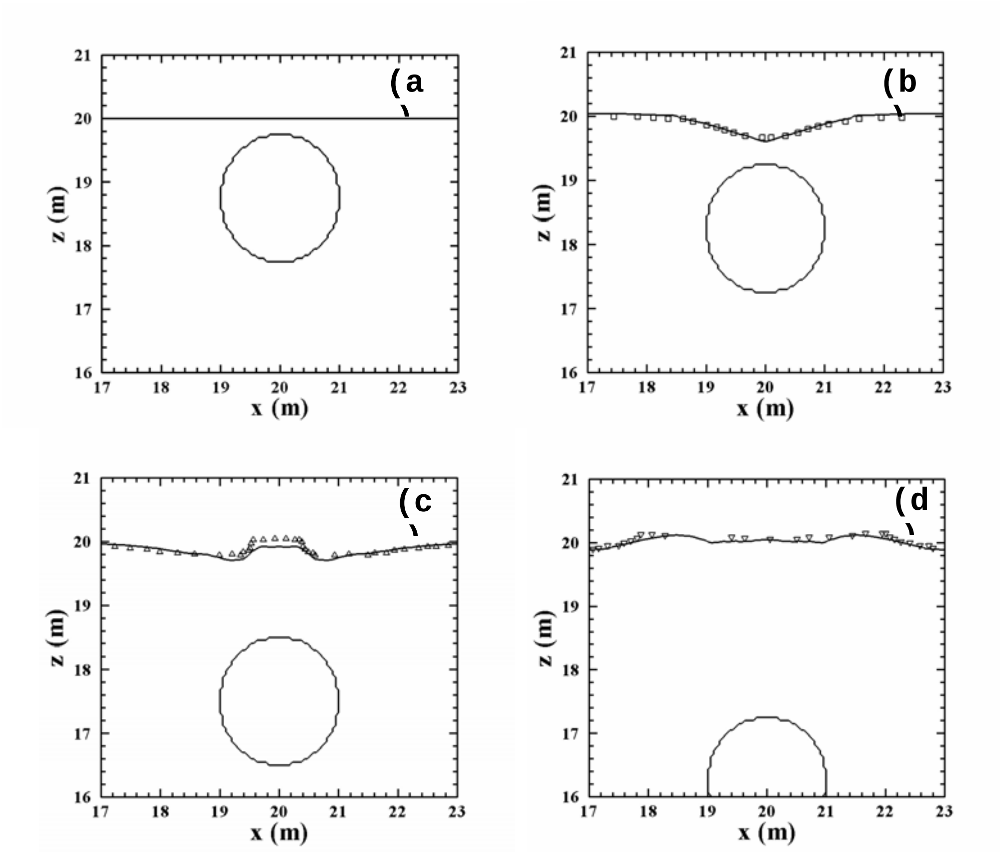

Figure 3. Water sinking of a horizontal cylinder. The simulated free surface profiles in the vicinity of the cylinder (—— solid line) compared to Lin (2007) numerical results (symbols); a) t = 0.00 s; b) t = 1.28 s; c) t = 3.20 s; d) t = 6.41 s.

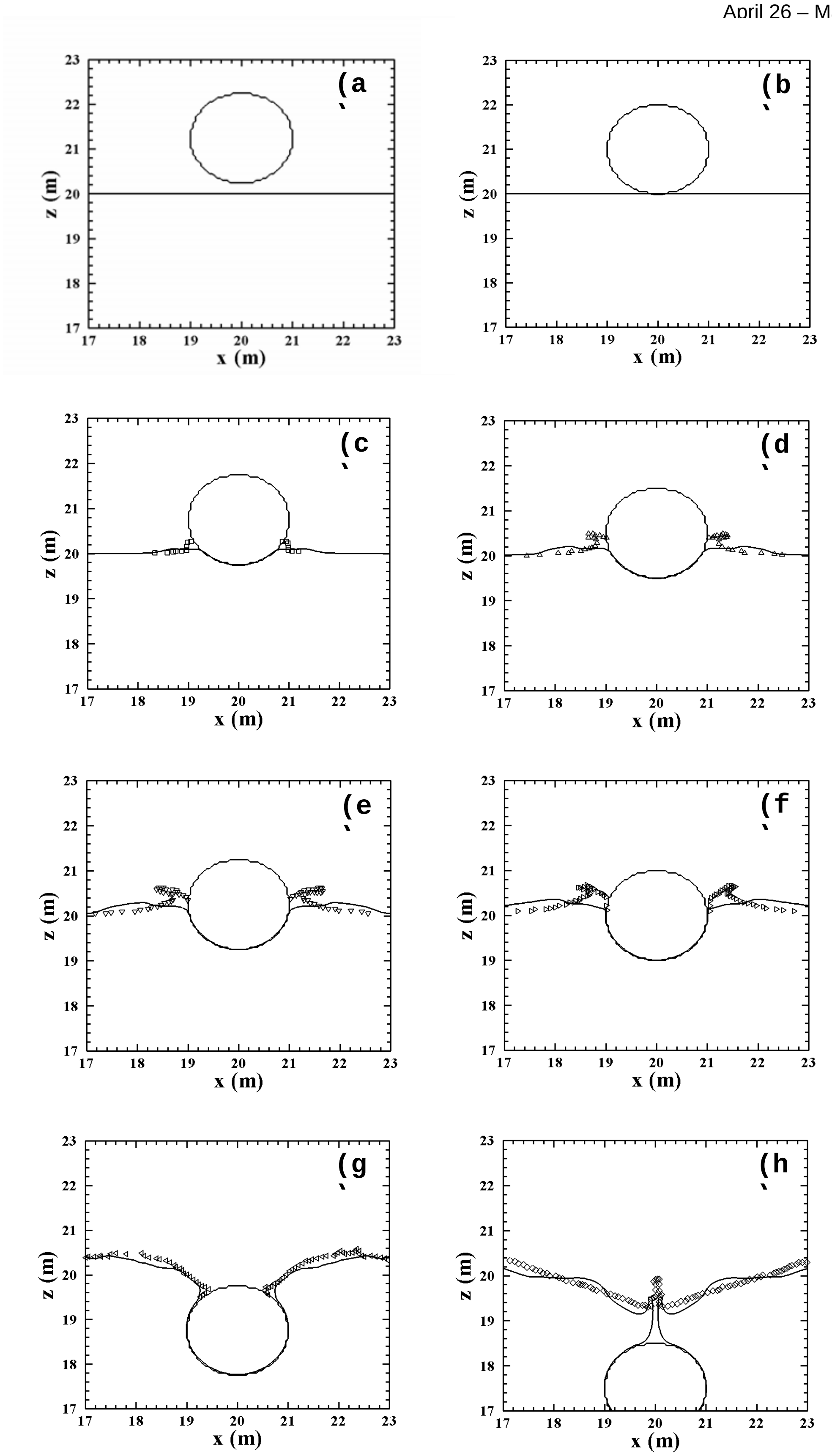

Figure 4. Water impact and entry of horizontal cylinder. The simulated free surface profiles in the vicinity of the cylinder (—— solid line) compared to Lin (2007) numerical results (symbols); a) t = 0.00 s; b) t = 0.25 s; c) t = 0.50 s; d) t = 0.75 s; e) t = 1.00 s; f) t = 1.25 s; g) t = 2.50 s; h) t = 3.75 s.