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CFD Simulation of Surge Wave Generated by Flow-Like Landslides

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***Abstract*—**The damage caused by surge waves generated in water bodies by flow-like landslides can be very high in terms of human lives and economic losses. The complicated phenomena occurred in this highly unsteady process are difficult to model because three interacting phases: air, water and sediment are involved. The problem therefore is challenging since the effects of non-Newtonian fluid describing the rheology of the flow-like landslides, multi-phase flow and free surface have to be included in the simulation. In this work, the commercial computational fluid dynamics (CFD) package FLUENT is used to model the surge waves due to flow-like landslides. The comparison between the numerical results and experimental data reported in the literature confirms the accuracy of the method.

***Keywords*—**Flow-like landslide, surge wave, VOF, non-Newtonian fluids, multi-phase flows, free surface flow.

I. Introduction

SURGE waves may be generated by landslides, snow avalanches, shore instabilities, and glacier and rock falls in geometrically confined water bodies such as reservoirs, lakes, estuaries and bays. Due to the steep slopes surrounding the water body and the density of the landslide material, the velocity of landslides-generated surge waves may be quite significant. This makes its potential destruction very high as these surge waves can overtop dams and destroy the downstream villages. As an example, the Vaiont disaster in 1963 killed about 2500 people for the dam was over-topped by as much as 245m of water wave [1]. The correct prediction of mechanism of generation, propagation and transformation of the surge wave can notably reduce losses inferred by these phenomena, as it provides a means for defining the hazardous areas, estimating the intensity of the hazard, and for working out the information for the identification and design of appropriate protective measures. Therefore, it is critical to develop a transient numerical model to simulate surge waves that may be generated by the sudden fall of landslide material into the water bodies.

This paper focuses on the landslide impact induced surge waves. Among landslides, flow-like landslides often result in catastrophic events as in the cases recorded in Japan (1998), China (1999), Venezuela (1999) and El Salvador (2001) [2], [3]. The distinctive features of this flow-like landslide are strictly related to the mechanical and rheological properties of the involved materials, which are responsible for their long travel distances (up to tens of kilometres) and the high velocities (in the order of metres/second) they may attain. Flow-like landslides are common in both subaerial and subaqueous environments. While torrential rains can trigger subaerial flow-like landslides [4], the oversteepening of a slope and liquefaction [5] are common causes of underwater flow-like landslides. In addition, seismic and wave loading may also trigger a subaqueous flow-like landslides. Whether subaerial or underwater, flow-like landslides may generate surface waves, large enough to cause significant hazard for downstream populations and infrastructures.

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Due to the complexity of the flow-like landslides process, a number of models were developed to simulate the flow behavior. In applications to real debris flows, single phase models are often used. This represents a simplification of a debris flow where the main constituents are water and solid material consisting of a wide range of grain sizes. Because the flow process is still poorly understood and the limits between different constitutive approaches can hardly be assessed for real mixtures, the application of simplified models such as single-phase models appears to be a reasonable first step towards a systematic application and evaluation of simulation. Several researchers have developed theoretical and numerical models of debris flows. Based on the rheology used to describe debris flow mechanics, Jiang and LeBlond [5] have classified these models into three groups: viscous models [6], viscoplastic models [7], and frictional models [8]. The linear viscoplastic Bingham model is most commonly used to describe the rheology of a debris or mud flow.

Experiments have been carried out to study aerial and subaerial landslides [9]-[12], but these may be both time-consuming and costly to carry out. By contrast, numerical modeling, if properly validated with laboratory experiments, may be a more flexible and efficient tool. Moreover, numerical modeling more easily provides flow variables for any point of space and, hence, is better suited to a detailed study of physical processes. During the last decade, a number of numerical models [13]-[15] were proposed to model flow-like landslide induced water waves. In this work, the commercial computational fluid dynamics (CFD) package FLUENT is used to model the surge waves due to flow-like landslides. The main advantage of CFD code is that it uses the full Navier–Stokes equations and provides a solution to the flow problem. Moreover, the CFD packages are applicable in very complex geometries. The CFD calculations shown here are based on simulated solutions to the full Navier-Stokes equations, carried out using FLUENT software. The prediction of the free surface in the package is based on the volume tracking method VOF. This method is developed to simulate highly nonlinear effects such as breaking waves at the interface. The debris flows are treated as a Bingham fluid. The results of the proposed CFD model were compared with experimental results of previous investigations and found that it can reproduce the experiments with an acceptable accuracy.

II. Numerical Method

We approximate the landslide material as a liquid thus the problem is schematised in a multi-phase (water, air and granulars) flow. In VOF model, the fields for all variables and properties in each control volume are shared by the phases and represent volume-averaged values, as long as the volume fraction of each of the phases is known at each location. Thus the variables and properties in any given cell are either purely representative of one of the phases, or representative of a mixture of the phases, depending upon the volume fraction values. The equations for conservation of mass and momentum in each control volume are given as follows [16]:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

$$\frac{\partial \vec{v}}{\partial t} + \nabla \cdot (\vec{v}\vec{v}) = -\frac{\nabla p}{\rho} + \nabla \cdot (\bar{\bar{\tau}}) + \vec{g} \tag{2}$$

where ρ, $\vec{v}$, p are respectively the density, velocity and pressure shared among the phases, $\vec{g}$ is gravity acceleration. For water, the shear stress is defined by $\bar{\bar{\tau}} = \mu(\nabla\vec{v} + (\nabla\vec{v})^T)$ with μ is the viscosity. For granular describing by Bingham plastics, the shear stress is given by $\tau = \tau_0 + \mu\dot{\gamma}$ where τ_0 is the yield stress and $\dot{\gamma}$ is the shear rate.

The tracking of the interfaces between the phases is accomplished by the solution of the continuity equation for the volume fraction α of one of the phases. For the *q*-th phase, this equation has the following form:

$$\frac{\partial \alpha_q}{\partial t} + \vec{v} \cdot \nabla \alpha_q = 0 \tag{3}$$

The volume fraction equation is not solved for the primary phase for which the volume fraction is computed by $\sum_{q=1}^{n} \alpha_q = 1$, the density in each cell is given by $\rho = \sum_{q=1}^{n} \alpha_q \rho_q$ and similarly the viscosity is given by $\mu = \sum_{q=1}^{n} \alpha_q \mu_q$. For $\alpha_q = 0$, the cell is empty of the *q*-th fluid. For $\alpha_q = 1$, the cell is full of the *q*-th fluid. For $0<\alpha_q<1$, the cell contains the interface between the *q*-th fluid and one or more other fluids.

A second order upwind interpolation scheme was used to obtain the face fluxes whenever a cell is completely filled with one phase or another. The geometric reconstruction scheme was used when the cell is near the interface between two phases. The geometric reconstruction scheme represents the interface between fluids using a piecewise-linear approach. It assumes that the interface between two fluids has a linear slope within each cell, and uses this linear shape for calculation of the advection of fluid through the cell faces.

III. Results and Discussion

In this section, A channel experiment by Rzadkeiwicz [17] was simulated using the proposed method. This experiment consists of generating water waves by allowing a mass of sand to slide freely down a frictionless inclined plane with a slope of 45° (Fig. 1). The channel is 4 m long, 0.30 m wide and 2 m high. The sand mass is as wide as the channel, so that the experiments are 2D in a vertical plane. The initial vertical profile of the sand mass is triangular. This mass is held in its initial position by a vertical water gate. This gate is lifted up very quickly at $t = 0$ s. The dimensions of this mass in cross section are 0.65 m x 0.65 m. The mean apparent density is 1950 kg/m^3. The water depth is 1.60 m and the top of the triangular mass is initially 10 cm below the water surface.

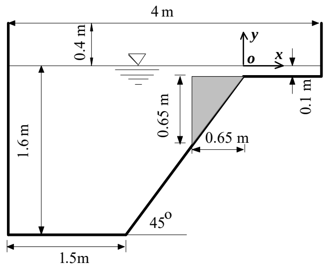

Fig. 1 Computational domain sand sliding into channel

The computational domain is 4 m by 2 m in *x* and y directions. The origin of the rectangular co-ordinate system is located at the water surface 10 cm above the intersection of the horizontal shore and the inclined plane. The mesh consists of 92400 quadrilateral cells with uniform spacing, the cell sizes in the *x* and y directions are 0.01 m.

In our simulation the landslide material was approximated as a Bingham plastics fluid, the problem is thus a three-phase (water, air and granular) flow. In CFD package FLUENT, you can specify the primary and secondary phases whichever way you prefer. It is a good idea to consider how your choice will affect the ease of problem setup. For example, if you are planning to patch an initial volume fraction of 1 for one phase in a portion of the domain, it may be more convenient to make that phase a secondary phase. In our case, the air is specified as the primary phase while the water and the landslide are specified as secondary phases. The Navier–Stokes equations coupling with VOF are solved in transient state, taking into account gravity forces. The operating pressure is set to 101325 Pa. The boundary conditions are: ''pressure outlet'' with gauge pressure at zero Pascal for the top side of the computational domain (see Fig. 1). The two lateral sides and the bottom are modeled as ''stationary wall''. The slip condition with zero shear stress is used to model the frictionless slope. The pressure based solver is chosen for the present numerical analysis. The velocity–pressure coupling is treated using the SIMPLE algorithm and the second-order upwind scheme is used for momentum. For greater accuracy, a value of 10^{-4} is used for all residual terms.

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Two simulations have been carried out using different rheological coefficients. For each case, the computed density maps are presented at t = 0.4 s, t = 0.8 s and t = 1.2 s. The digitized experimental wave profiles are compared with the numerical ones at t = 0.4 s and t = 0.8 s. In both case, the viscosity of the air is 1.8×10^{-5} Pa.s while the density is 1.225 kg/m^3. The viscosity of the water is 1.8×10^{-3} Pa.s while the density is 998 kg/m^3. The granular flow are modeled by a Bingham fluid of density 1950 kg/m^3. At the interface between ambient water and granular flow, no friction is computed. Simulations have been performed with yield stress τ_0 = 200 Pa and τ_0 = 1000 Pa respectively. In both case, the viscosity μ is set to 0 assuming that granular is liquefied as soon as the yield stress is exceeded.

Figs. 2 and 3 respectively show the numerical results for the two yield stress values. For both cases at t = 0.8 s, a part of the mass is located at the top of the slope, but the most important mass is still concentrated at the mud front. In the simulation where the value of yield stress τ_0 is higher, the granular mass is so rigid that it almost keeps its initial shape. As it can be observed on the density maps, the wave amplitude and the slide velocity depend on the yield stress of sand.

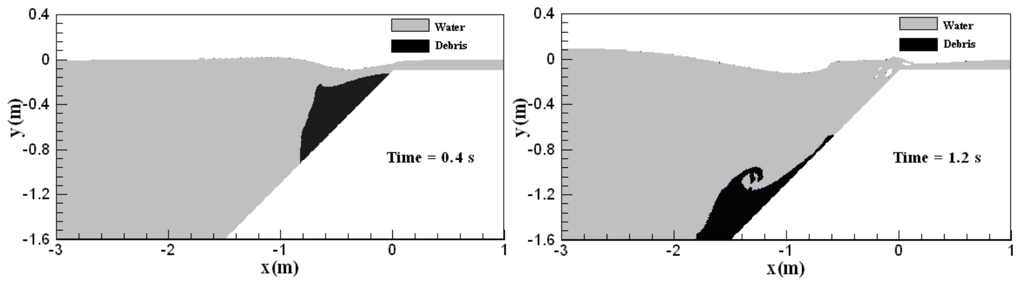

Fig. 2 Computed density at t = 0.4 s and t = 1.2 s (τ_0 = 200 Pa)

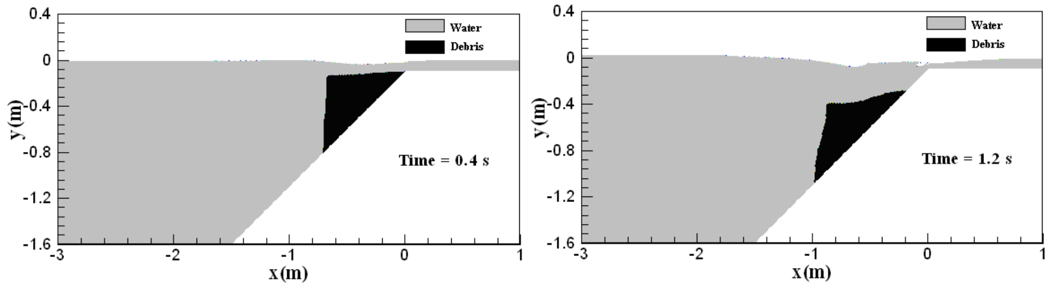

Fig. 3 Computed density at t = 0.4 s and t = 1.2 s (τ_0 = 1000 Pa)

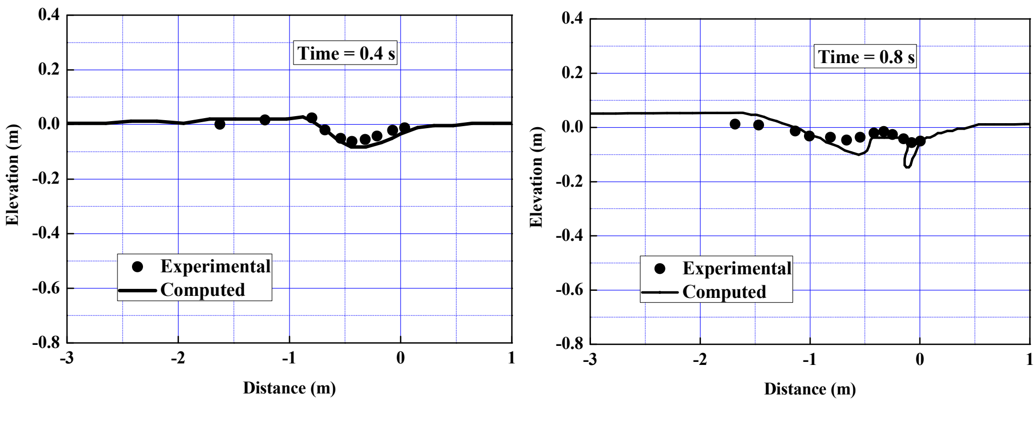

Fig. 4 Comparison of experimental and computed free surfaces at t = 0.4 s and t = 0.8 s (τ_0 = 200 Pa)

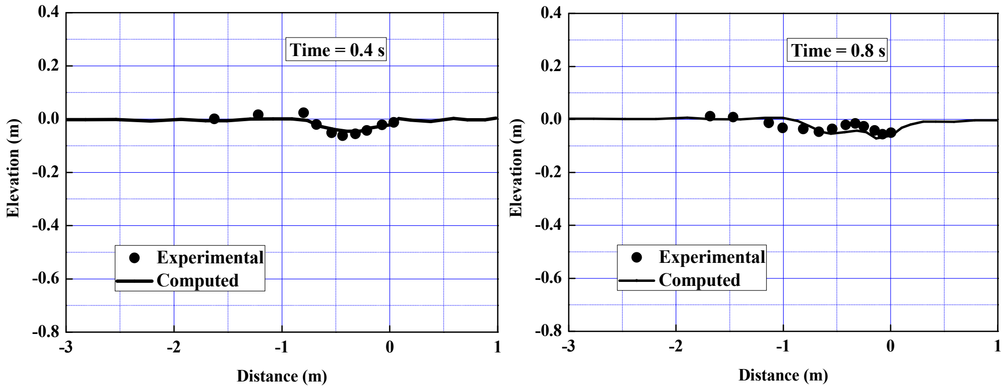

Fig. 5 Comparison of experimental and computed free surfaces at t = 0.4 s and t = 0.8 s (τ_0 = 1000 Pa)

Figs. 4 and 5 respectively show the comparison between experimental waves and computed waves for the two yield stress values at t = 0.4 s and t = 0.8 s. As it can be observed on the density maps at t = 0.8 s, the slide with a larger yield stress moves much more slowly and generates smaller waves close to the recorded ones.

IV. Conclusion

In the present study, a 2-D numerical model developed in the CFD package FLUENT is applied to simulation of the surge waves by flow-like landslides. In the proposed procedure, the full Navier–Stokes equations coupling with the Volume of Fluid method tracking free surfaces is solved and the mechanical behavior of debris flow is described by a Bingham law. The numerical parameters, i.e. the plastic viscosity, the Bingham yield stress and the friction coefficient have been selected to match the experiment. The results of the proposed CFD model were compared with experimental results of previous investigations and found that it can reproduce the experiments with an acceptable accuracy. Although the present study was limited to a two dimensional analysis, the proposed procedure can be extended to deal with realistic three dimensional problems that are of great interest for civil engineering because the CFD packages are applicable in very complex three dimensional geometries.

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