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A three-phases model for the simulation of landslide-generated waves using the improved conservative level set method

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ABSTRACT

This paper introduces a three-phases model based on the finite element method to simulate the generation and propagation of landslide-generated impulse waves, and this model can be employed to predict and prevent wave-induced hazards. The fluid-like landslide mass is treated as a non-Newtonian viscoplastic fluid. The motion of landslides, water and air is modelled by the incompressible Navier–Stokes equations and the interfaces between these three phases are captured with the *n*-phases improved conservative level set method which can preserve mass and provide precious interface parameters, including normals and curvatures. The conservative feature of this method is proven by the three-phases Zalesak slotted disk test case. This method is then adopted to simulate the impulse wave generated by the Lituya Bay landslide and the current outputs are compared with other existing results. Finally, this verified model is utilized to model the impulse waves generated by the Halaowo landslide near the Xiangjiaba Dam in the Jinsha River and the results could provide references for further protective activities.

1. Introduction

Landslides are frequent and severe geological activities which can lead to disastrous damage. Compared with landslides which slide in an open area, those impacting into a reservoir could cause more catastrophic consequences because of the generated destructive waves. In extreme situations, waves could overtop a dam and inundate vast areas along the shoreline. One of the deadliest disasters is the Vajont Reservoir landslide in 1963. The landslide mass generated a wave with a height of 250 m and claimed around 2000 lives. It is worth noting that there are tremendous potential landslides in reservoirs due to the frequent change of water levels. The Shanshucao landslide (about $4 \times 10^7 m^3$), which is one of 3028 landslides observed in the Three Gorges Reservoir in China, lost stability and destroyed a local hydropower station in 2014. Considering the large number of potential landslides existing in proximity of reservoirs and the severe losses, it is of great importance to carry out research on landslide-generated waves to predict the slide path of the unstable mass, the inundation area of waves and the overtopping possibility. Based on the predictive work, corresponding preventions should be performed, including slope reinforcements, controlled blasting of parts of the slide and early warnings of possible disasters.

Most of the existing researches about landslide-generated waves can be classified into four categories, analytical equations, physical experiments, numerical simulations and empirical estimations derived from field data, physical experiments or numerical simulations. In the initial stage, analytical equations [1,2] are proposed to estimate wave parameters roughly. The estimations are determined by simplified assumptions of landslides, water and topography and the results could vary over an order of magnitude by applying different hypotheses. To study the general behaviour of landslides and generated waves, laboratory experiments [3–9] in both two-dimensions (wave flume geometry) and three-dimensions (wave basin geometry) are performed. However, it consumes abundant time, labour and money when more experiments should be carried out due to the application of different parameters. Moreover, the accuracy of results could be influenced by scale effects [10] and results cannot be recorded in all points.

To lower the entire cost and study the characteristics of landslides and waves in detail, numerical simulation methods attract the attention of researchers around the world. Initially, numerical simulations of landslide-generated waves are made under different assumptions due to the complexity of this problem and the limitation of the computer capacity. Depending on the hypothetical degree adopted to describe the movement of the wave in numerical models, the mathematical formulations can be divided into four types, namely, shallow water equations (SWEs) [11–13], Boussinesq-type wave equations (BWEs) [14–16],

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potential flow equations (PFEs) [17,18] and the Navier-Stokes equations (NSEs) [19–23]. Among these methods, the general SWEs methods are appropriate for the simulation of the wave propagation process but are weak in representing the drastic phenomena during the wave generation process since the vertical acceleration is ignored. This shortcoming can be resolved by some improved wave models, including SWASH (Simulating WAves till SHore), which considers the effect of the vertical acceleration by the added non-hydrostatic pressure gradient. BWEs and PFEs models are applied to improve the order of accuracy. However, most of these existing BWEs and PFEs models are used to simulate rigid landslides by treating the landslide mass as moving boundary and ignoring the strong coupling between different phases. Compared with the former three models, NSEs models behave better in accuracy and application range. According to the conceptualization of landslides, some of the numerical models [24–26] treat the landslide mass as a rigid body and set the slide kinematics in the mass centre. However, this assumption is idealized as almost all actual landslides would deform in the sliding stage. In most cases, many physical experiments and numerical simulations have found that the wave height would be overestimated when treating the landslide as a rigid body [27–29]. However, an opposite phenomenon can be observed when there is no smooth transition at the toe of the slope [8]. In this situation, rigid slide may stop immediately whilst a granular slide runs-out further and thus transforms more energy to the wave. It is more accurate to take the deformability into consideration, especially when the landslide mass deforms drastically.

After the milestone study carried out by Quecedo et al. [30], the three-phases model gained more and more attention since it avoids the two assumptions mentioned above, namely the neglect of the vertical acceleration and the strong coupling between different phases. NSEs were applied to model the motion of landslides, water and air, which are three phases included in the landslides penetration stage, and the Level Set (LS) method was used to capture interfaces between different phases. The main advantage of this method lies in the fact that the strong coupling between landslides, water and air is considered, while the air phase is seldom taken into consideration in previous studies. Besides, they suggested that the non-Newtonian viscoplastic fluid model, which is a fluid-like model, can be utilized to model landslides when the slide mass slides down with a high speed. Considering the high moisture content and thick alluvium deposits of slopes in reservoirs, it is appropriate to treat this kind of landslides as fluid-like. Based on the three-phases model, many researchers [21,31] improved the simulation accuracy of the landslide-generated waves and extended the calculation to subsequent stages, including wave propagation and run-up. As the study objects herein are waves generated by landslides in reservoirs, the three-phases model, which treats landslides as fluids, is adopted in this paper.

When the three-phases model is employed to simulate landslide-generated waves, an accurate and efficient technique for the description of interfaces is crucial since interfaces could undergo drastic changes, including breaking, overturning and merging, caused by the strong interaction between different phases. It remains challenging to provide a conservative interface representing method, which can describe interfaces accurately. Typical methods of describing interfaces include Smoothed Particle Hydrodynamics (SPH) [32–35], Volume of Fluid (VOF) method [36–38] and the LS method [39,40]. Even though SPH method is widely known as a numerical technique which is able to solve the partial differential equations, it can also be used to represent interfaces. SPH is able to enhance the conservative property without advection errors within the entire calculation process. However, SPH has a high demand in computational cost and the modelling of boundary conditions is challenging. Besides, SPH method is unstable when tracking interfaces with large deformations. VOF method also exhibits excellent mass conservation property, but it needs complicated interfaces reconstruction. Meanwhile, it is challenging to calculate normals of interfaces exactly with VOF method because of the discontinuity of the applied color function. Compared with these two methods mentioned above, the LS method is simply and efficient to capture the front, while mass loss happens when advecting and re-initializing the indicator function. To improve the LS method, Olsson and Kreiss [41,42] proposed a mass conservation method, which is named as the conservative Level Set (CLS) method. Even though the mass conservation property of the advection step can be ensured, both the normals and curvatures of interfaces are sensitive to small spurious oscillations because of the intrinsic shortage of the Heaviside function. Hence, the CLS method cannot provide precise normals and curvatures of interfaces, which should be used in the re-initialization process. Combining the advantages of the LS method and the CLS method, the improved conservation Level Set (ICLS) method, which can represent interfaces in a conservative way, was proposed by Zhao et al. [43,44]. However, this method can only be used to capture the interface of two-phases flow until now.

In this paper, a three-phases model for the simulation of landslide-generated waves is proposed. This model applies a proper rheological model, namely the non-Newtonian viscoplastic fluid model, to describe the deformable fluid-like landslide mass and employs NSEs to simulate the motion of the three phases in the penetration region. To model three phases in the generation of landslide-generated waves, the previous ICLS method needs to be expanded from two-phases to n-phases. All the governing equations are discretized with the characteristic-Galerkin procedure. Compared with previous publications, this new model can represent interfaces more accurately by utilizing the expanded n-phases ICLS method, which can provide precise interface characteristics and preserve mass conservation property.

This paper is organized as follows. In Section 2, the governing equations, constitutive equations and the implementation of the ICLS method for n-phases flows are described. In Section 3, the numerical schemes including the characteristic-Galerkin procedure, discretization of NSEs and ICLS functions are shown in detail. In Section 4, the mass conservation property of this proposed method is verified by a benchmark test, namely the three-phases Zalesak slotted disk. Then, the proposed method is validated by comparing the current simulation outputs of the Lituya Bay landslide waves with the existing published results. Subsequently, this verified method is employed to predict impulse waves generated by the Halaowo landslide in the Xiangjiaba Reservoir. At the end of this paper, in Section 5, the conclusions are given.

2. Mathematical model

2.1. Governing equations

Considering immiscibility of the three phases interacting with each other, the viscous incompressible NSEs are employed to govern their motion:

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\frac{\partial \boldsymbol{u}}{\partial t} + \nabla \cdot (\boldsymbol{u} \otimes \boldsymbol{u}) = \frac{1}{\rho}\nabla \cdot \boldsymbol{\tau} - \frac{1}{\rho}\nabla p + \boldsymbol{f}_b \tag{2}$$

where ∇ represents the gradient operator, $\boldsymbol{u}$ indicates the velocity vector, t is time, $\boldsymbol{\tau}$ is the viscous stress tensor which is given in Section 2.2, p represents the pressure and $\boldsymbol{f}_b$ indicates the body force. Other forces not mentioned are not involved in the simulations in this paper. The material properties, such as density ρ, are determined in Section 2.3.