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Investigation of non-deformable and deformable landslides using meshfree method

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ABSTRACT

In this study, a meshfree method is introduced to simulate various types of landslides. Special attention was paid to the impact wave and sediment deformation due to their importance to the environment and human society. A multiphase model was applied in the meshfree method to reproduce two different phases. Different gradient models were compared and proper operators were selected to adapt the meshfree method for multiphase flow simulation. A widely used rheology model was utilized to represent the behavior of the non-Newtonian fluid in the deformable landslide cases. Non-deformable and deformable landslides are both simulated as typical landslide cases in this study with consideration of submerged and unsubmerged conditions. Good agreement between present numerical results and previous experimental or numerical results from the literatures indicated the present meshfree method is able to predict the impact wave and sediment deformation generated by the landslide, and thus, this model is capable of forecasting the flood and catastrophic impacts of landslides.

1. Introduction

Landslides are complex natural phenomenon that usually occur near mountains, oceans, bays, and reservoirs (Dong et al., 2010; Heller and Hager, 2011; Heller and Spinneken, 2013). Generally, soil coasting, rock falling, and debris sliding are recognized as typical landslides, which usually start on a slope and eventually fall into the water bodies such as oceans, lakes, and bays (Abadie et al., 2010; Fall et al., 2006; Heinrich, 1992; Kamphuis and Bowering, 1972). Considering the deformation of the sliding block, landslides can be recognized as non-deformable landslides or deformable landslides, while based on the initial sliding position, landslides can also be classified as submerged landslides and unsubmerged landslides. Few previous studies have paid attention to systematic research of landslides based on the combination of different conditions that reflects most of the nature landslide types. In this study, a meshfree Lagrangian method is introduced to study various types of landslides, and special attention is paid to the impact wave and sediment deformation, which are both considered as the main factors in the nature impacts caused by landslides (Ataie-Ashtiani and Shobeyri, 2008; Capone et al., 2009; Najafi-Jilani and Ataie-Ashtiani, 2008; Ramadan et al., 2014).

As an important phenomenon in hydraulics and geotechnics, landslides have been studied extensively. Focus is typically on the waves generated by the landslide within the nearby area (Dong et al., 2010; Heller and Hager, 2011). The landslide waves or tsunamis in lakes, oceans, and bays may lead to serious floods in the nearby shore area and result in catastrophes (Ramadan et al., 2014; Rzadkiewicz et al., 1997; Kamphuis and Bowering, 1972). Meanwhile, the sediments, rocks, and clays carried by the landslide may change the terrain and the morphology of the damaged zones (Rzadkiewicz et al., 1997; Sue et al., 2011; Watts, 1998). Hence, over the recent centuries, researchers have made continuous efforts to further understanding of landslides and minimize the damaging impacts of the vast affected areas.

Considering previous studies on landslides, besides field observations, numerous experimental and numerical studies have been conducted to identify the characteristics of landslides (Zweifel et al., 2007, 2006; Cremonesi et al., 2010, 2011). Most of the physical landslide models conducted in the laboratory are small scale, and thus, some of the landslide characteristics are missing due to the fact that some of the physical characteristic of the landslide are only available to be captured in large-scale models. Although the physical models of landslides are usually in small scale, they always involve a long period to complete different experimental setups, the post-process of the experiments is also time-consuming (Rzadkiewicz et al., 1997; Cremonesi et al., 2010). With the development of the computational technology, the numerical study of landslides has become attractive due to its simplicity and efficiency (Zweifel et al., 2007). Multiphase flow modeling is usually required in numerical landslide models to investigate the phenomenon of the landslide. Numerical

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assumptions are sometimes introduced to further simplify the model with minor deteriorations of the simulation results (Zweifel et al., 2007, 2006). Additionally, when considering deformable landslide simulation, rheology models become important, as in most of the numerical studies of landslides, the prediction of the motion and deformation of non-Newtonian fluids such as soils and clays relies on the rheology model (Watts, 1998).

Traditionally, the Eulerian mesh-based numerical models have dominated the computation of landslides due to its maturity (Zweifel et al., 2007, 2006). The velocity, pressure, and fluid interface can be calculated and reproduced on nodes. For landslide studies, the mesh-based model shows disadvantages in predicting the impact waves and the block movements, both of which are represented by the simulated interface between different phases during the computation (Rzadkiewicz et al., 1997; Cremonesi et al., 2010). Because of the importance of reproducing the interfaces in numerical studies of landslides, the meshfree Lagrangian model is considered as a powerful alternative to simulate the landslide. The Lagrangian meshfree method uses particles instead of meshes as the basic simulation elements. These particles are not only used to discretize the simulation domain, but also to calculate the fluid flow characteristics (Fu and Jin, 2014; Hosseini et al., 2007). The wave profile and the deformation of the sediments are important in the study of landslide and most of previous studies in a mesh-based method required special numerical treatment such as VOF (Volume Of Fluid) to locate the interface between air and water or the interface between water and sediment. While in MPS method, particles are used as basic simulation elements, the interface can be track easily due to the inherent advantages of MPS method, additional numerical treatment is unnecessary during the simulation and the interface tracking become easier in MPS method than in the traditional mesh-based method.

Similar to previous numerical studies of landslides, multiphase model as well as rheology model are both required in the Lagrangian meshfree method in landslide simulation. For the rheology model, some previous studies have successfully introduced simple rheology models in a Lagrangian based meshfree method. Shakibaeinia and Jin (2011) have simulated water-sediment dam break by the meshfree method, and Hosseini et al. (2007) introduced a simple rheology model to simulate non-Newtonian fluid. In this study, a Lagrangian-based multiphase model with a Herschel–Bulkley rheology model is used to represent the characteristics of the non-Newtonian fluid in landslide simulation. In addition, extra numerical efforts are made to minimize the interface instabilities and pressure oscillations. With this developed multiphase model, both the non-deformable and deformable landslides considering different initial conditions, namely submerged and unsubmerged initial conditions, have been successfully reproduced in a meshfree Lagrangian method, which may improve the prediction of landslides in the real world.

2. Methodology

2.1. Governing equation

The MPS (Moving Particle Semi-implicit) method is a fully Lagrangian meshfree particle-based method that was first developed by Koshizuka et al. (1995). This method has been adapted to various types of fluid flow simulations in recent years. The governing equation in MPS method is in a fully Lagrangian frame, considering the landslide simulation in this study, the governing equation used in this study is given as (Cremonesi et al., 2011; Monaghan and Kos, 1999):

$$\frac{1}{\rho}\frac{D\rho}{Dt}+\nabla\mathbf{u}=0 \tag{1}$$

$$\rho\frac{D\mathbf{u}}{Dt}=-\nabla p+\nabla\tau+\rho\mathbf{f} \tag{2}$$

where ρ is the fluid density, $\boldsymbol{u}$ is the velocity factor, p is the pressure, τ is the stress, and $\boldsymbol{f}$ is the body force and is usually considered only as the gravity force. Since a multiphase model is used, the variation of sediment viscosity becomes critical. The viscosity is kept as a constant in water phase but it becomes a variable in the sediment phase during the simulation. Therefore, in the above governing equation, calculation of the stress term $\nabla\tau$ will be important in the simulations near the interface and in sediment phase, but will be simple in the water phase.

Since the MPS method is similar but different from another famous meshfree particle method SPH, the discretizations of gradient and Laplacian in the governing equation also show differences compared to the SPH method although the computation algorithm are similar in both methods. Additionally, some of the SPH methods use artificial density or viscosity terms to deal with the density or viscosity variation while most of the MPS methods use Poison equation or equation of state to solve the density variation. In this study, the discretizations of the operators in the governing equation differ from the traditional mesh-based method, the gradient term and the Laplacian term are discretized using the MPS formula, and the general gradient (or divergence) model and Laplacian model in MPS are given as (Khayyer and Gotoh, 2013; Lee et al., 2008; Shibata et al., 2004; Yim et al., 2008):

$$\nabla\phi=\frac{d}{n_0}\sum_{i\neq j}\left(\frac{\phi_\iota-\phi_j}{\left|r_j-r_i\right|^2}\right)(r_j-r_i)W(r_i,r_j) \tag{3}$$

$$\nabla^2\phi=\frac{2d\int_V W(r_i,r_j)dv}{\int_V W(r_i,r_j)r^2dvn_0}\sum_{i\neq j}\left(\phi_i-\phi_j\right)W(r_i,r_j) \tag{4}$$

where d is the space dimension, r_i and r_j are the particle position vector, and ϕ_i, ϕ_j are the general scalars or vectors of particles i and j, respectively. n_0 is the initial particle number density, and the particle number density is given by (Souto-Iglesias et al., 2013; Lee et al., 2008):

$$n_i=\sum_{j\neq i}W(r_i,r_j) \tag{5}$$

With the above MPS operators, the pressure gradient term and velocity Laplacian term in the governing equation can be calculated in the MPS frame. The kernel function W is used in MPS method to represent the spatial relationship among particles, which is indeed a mimic function of Dirac Delta function (Wendland, 1995). In this study, a third order spline kernel is used, which is given as (Fu and Jin, 2013):

$$W(r_i,r_j)=\begin{cases}\left(1-\frac{|r_i-r_j|}{R_a}\right)^3 & |r_i-r_j|\le R_e\\ 0 & |r_i-r_j|>R_e\end{cases} \tag{6}$$

where r_i, r_j are the position factors and R_e is the searching radius. A simple MPS sketch including the utilizations of kernel function, searching radius, and effective particles are shown in Fig. 1.

Originally, the MPS method was developed as a fully incompressible model. However, the implicit pressure calculation requires a matrix that will cost most of the simulation time to solve the huge matrix if a large number of particles are used. In this study, a weakly compressible method is introduced in the MPS method in order to simplify the pressure calculation and enhance the simulation efficiency. The weakly compressible model is also used in the SPH method (Lee et al. 2008). Similar but different from the weakly-compressible SPH method, the developed weakly compressible MPS pressure calculation is given as (Lee et al., 2008):

$$p_i^{n+1}=\frac{\rho c_0^2}{\gamma}\left(\left(\frac{\sum_{j\neq i}W(r_i,r_j)}{n_0}\right)^\gamma-1\right) \tag{7}$$