

Study on post-failure evolution of underwater landslide with SPH method

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Abstract

Underwater landslide is a serious nature hazard which could occur at both sea floor and reservoir banks and results in massive destruction. It generally involves large deformation of landslide and water body, especially the interface between them. A numerical model for describing the soil-water interface and its large deformation in the framework of smoothed particle hydrodynamics (SPH) method is employed to simulate the evolution of underwater landslides. The elasto-plastic-viscous model with Drucker-Prager plastic yield rule is used for soil deformation simulation. And the direct forces exchange between interfacial soil and water particles is implemented to characterize the interface deformation. Both quasi-steady and dynamic behaviors of soil and soil-water interface during underwater landslide post-failure stage are revealed. Simulated results shows that the landslide body experiences strong deformation during the impact process.

Keywords: underwater landslide, soil-water coupling, interface, smoothed particle hydrodynamics.

Introduction

Underwater landslide could occur at both sea floor and reservoir banks, causing massive destruction. In this hazard, the underwater landslide failures during earthquake or underwater excavation or all kinds of porous pressure accumulation. The plastic bands will form in the landslide body and cause fast movement of the landslide like it in subaerial landslides. However fast opposite movement of landslide body and water surrounding it is a unique feature comparing with subaerial landslides. As the density of landslide body and the water is basically in the same magnitude order comparing with the subaerial landslide, the water resistance effect is much stronger than it of subaerial landslides. Thus the interface between slide and water must be considered in the simulation. What is more, this process also involves very large deformation of the landslide and water body, especially the interface between them. If we ignore the seepage force in the landslide body which might always be true for fine grain soil, the problem is basically dealing with a gravity controlled deformable interface between soil and water. So, two crucial characteristics, i.e. the soil-water interfacial coupling and large deformation of interface, should be well addressed in the simulation of the underwater landslides evolution process.

However these two features raise great challenge to classical mesh based simulation methods such as FEM due to the large deformation nature. Many studies simplify this problem into the interaction between two fluids, i.e. Newtonian fluid and non-Newtonian fluid, and thus both mesh based FVM with VOF interfacial model and mesh-free methods such as SPH could be employed. Rzedkiewicz et al. [1] have used such an approach to simulate the landslide generated wave problem. However, the non-Newtonian model for granular flow is not designed for quasi-steady problems as the static stress state could not be represent truly due to its fluid nature, thus could not been used to predict not only the failure form of the slope but also localized particle-solid state during the slide evolution. As geo-engineers often prefer

elasto-plastic models for landslide simulation which could describe the quasi-steady state of soil very well, a coupled model including elasto-plastic-viscous soil model and Navier-Stokes equation based fluid model with an interaction model between soil and water is the best choice. Thus a recently developed mesh free soil-water coupling model which could deal with both quasi-steady and dynamic behaviors of soil, water and the interface is employed in the framework of smoothed particle hydrodynamics method.

Numerical Model for Soil

The model is constituted of three parts: model for soil, model for water flow, and model for the interface between. Different with non-Newtonian models which are commonly used for granular flow simulation, this study employs the elasto-plastic-viscous model for soil deformation simulation as the latter could reproduce more phenomena in landslide evolution, i.e. from stable state to granular flow. The steady state is ruled by elastic model, while the quasi-steady state is ruled by plastic model with Drucker-Prager plastic yield criterion. The post-plastic behavior of soil (particle-fluid state) is modelled with the plastic-viscous model which is similar with non-Newtonian models. This model could also profit from extensive existing constitutive laws and plastic yield rules which all have large amount of experimental data to support. Pioneering work of Bui et al. [2] has introduced SPH method into the elasto-plastic simulation of soil slopes. Following Bui's work, this study uses similar approach for landslide simulation, the detailed equation is list below:

$$\frac{D\rho_i}{Dt} = \sum_{j=1}^N m_j (v_i^\alpha - v_j^\alpha) \frac{\partial W_{ij}}{\partial x_i^\alpha} \quad (1)$$

$$\frac{Dv_i^\alpha}{Dt} = \sum_{j=1}^N m_j \left(\frac{\sigma_i^{\alpha\beta} + \sigma_j^{\alpha\beta}}{\rho_i \rho_j} - \Pi_{ij} \delta^{\alpha\beta} + F_{ij}^n R_{ij}^{\alpha\beta} \right) \frac{\partial W_{ij}}{\partial x_i^\beta} + g^\alpha \quad (2)$$

where $F_{ij}^n R_{ij}^{\alpha\beta}$ is the artificial stress term, helping to remove the tensile instability when soil is stretched; $F_{ij} = W_{ij} / W(\Delta x, h)$, and the exponent n is set as 2.55 in this paper.

$R_{ij}^{\alpha\beta} = R_i^{\alpha\beta} + R_j^{\alpha\beta}$ where $R_i^{\alpha\beta}$ and $R_j^{\alpha\beta}$ are the components of the artificial stress tensor for particles i and j , respectively. $\sigma^{\alpha\beta}$ is the total stress tensor, while the elastic-plastic soil constitutive model with the Drucker-Prager criterion can be expressed as:

$$\frac{D\sigma_i^{\alpha\beta}}{Dt} = \sigma_i^{\alpha\gamma} \dot{\omega}^{\beta\gamma} + \sigma_i^{\gamma\beta} \dot{\omega}_i^{\alpha\gamma} + 2G\dot{\epsilon}_i^{\alpha\beta} + K\epsilon_i^{\gamma\gamma} \delta_i^{\alpha\beta} - \dot{\lambda}_i \left[3\alpha_\psi K \delta^{\alpha\beta} + \frac{G}{\sqrt{J_2}} s_i^{\alpha\beta} \right] \quad (3)$$

where $\dot{\epsilon}^{\alpha\beta}$ is the deviatoric shear strain rate tensor, $\dot{s}^{\alpha\beta}$ is the deviatoric shear stress rate tensor, $\delta^{\alpha\beta}$ is Kronecker's delta. $\dot{\lambda}$ is the rate of the plastic multiplier λ dependent on the state of stress and load history:

$$\dot{\lambda}_i = \begin{cases} \frac{3\alpha_\phi K \dot{\epsilon}_i^{\gamma\gamma} + (G/\sqrt{J_2}) s_i^{\alpha\beta} \dot{\epsilon}_i^{\alpha\beta}}{9\alpha_\phi \alpha_\psi K + G} & f(I_1, J_2) = 0 \\ 0 & f(I_1, J_2) < 0 \end{cases} \quad (4)$$

where the $\dot{\epsilon}^{\alpha\beta}$ and $\dot{\omega}^{\alpha\beta}$ are the elastic strain rate tensor and the spin rate tensor, respectively. $f(I_1, J_2)$ is the yield function, I_1 and J_2 are the first and second invariants of the stress tensor, respectively; α_ϕ and k_c are Drucker-Prager's constants, which are related to the Mohr-Coulomb material constants c (cohesion) and ϕ (internal friction), and α_ψ is a dilatancy factor related with the dilatancy angle.

Numerical Model for Water and Soil-Water Coupling

The traditional weak compressible SPH model is used for modeling water flow. The artificial viscosity model calibrated with Viroulet et al.'s [3] experiment is employed to describe the viscous effect as we found that laminar+SPS model could not give better results for this complex problem with limited particle sizes. For example, if we choose the sub-particle scale viscosity model, we need at least 0.04mm spatial resolution in the first case to make the first grid space from boundaries located in logarithmic zone ($y^+ \sim [10-100]$). This resolution will make the calculation cost unbearable even if we can handle the numerical viscosity properly so as to not overestimate the viscosity in other zones. Secondly, although the viscosity of water is important in the underwater landslide evolution problems, its influences concentrate in the shear stress between water and soil. While the normal stress might play a more important role in describing the soil deformation, especially when the soil is modeled as an elasto-plastic-viscous material which is "stiffer" than Bingham fluid. Thus, although introducing the artificial viscosity may not be elegant enough, but neither it is notably worse than other choices nor it alters the significance of interactions between soil and water, especially in the situation of this study.

The interfacial coupling method is crucial for this problem. We use explicit time evolution scheme and the consistency of both the displacement of the interface and the pressure on the interface to setup the coupling model (Fig. 1). The displacement of interfacial particles is determined by the soil phase calculation while the stress on the interface is corrected to represent the effect of water pressure. Then the obtained displacement is used as the displacement of the interfacial moving wall for water phase calculation. As dynamic boundary condition is employed for wall boundaries, we simply use the interfacial soil particles to act as boundary particles for water phase to support the water calculation. Thus, we can directly obtained force pairs between water and boundary particles. These force pairs is exactly the same as them between water particles and the interfacial soil particles. So we can use them to correct the interfacial stress for the soil phase calculation. In this way, a direct coupling model is implemented in the framework of SPH method. Although this method is very simple, but due to its external interfacial coupling nature, it is robust and easy to extend to more complex situation such as considering three phases or rigid stones.

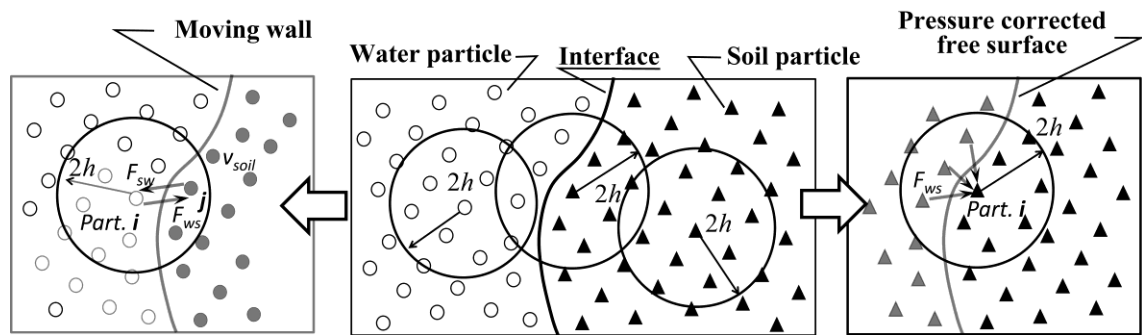


Figure 1. Illustration of the coupling model

Model Validation and Application on Underwater Landslide

Fritz et al.'s (2009) [4] laboratory experiment is used to validate this model and good agreements between simulated results and experimental data are obtained on slide shape evolutions, as shown in Fig. 2. We can see that although the simulated result is slightly different from experiment at the bottom of the slide: the simulated result has water cushion at the head of slide while it is not observed in the experiments, the simulated slide head position

and the thickness is similar to the experimental data which proves the validity of this model applying on the soil-water coupling simulation.

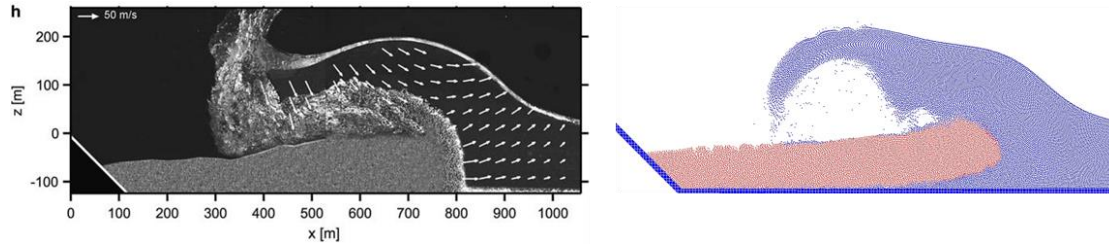


Figure 2. Comparison of simulated result and Fritz's experiment

The proposed model is used to study the subaqueous landslide evolution. We choose a typical experiment work on underwater landslide evolution by Rzedkiewicz et al. (1997) [1]. A submerged triangle slide made of fine-grain sands is placed on a 45° slope and a vertical board is placed at one end of the slide to keep it steady. When the board is suddenly removed, the landslide body collapses. The lower part of the landslide body deforms firstly, and the left part of the landslide body moves afterwards. In this process, the interaction force between grain landslide and water phase results in large deformation of the head of the landslide body.

The comparison of experimental snapshots and results from the proposed model is shown in Fig. 3a,b. The accumulated plastics strain (ADPS) which could be considered as an indication of the shear-induced plastic band is shown in simulated results. It is clear that the plastic zones are located at two interfaces: (1) interface between the slide and the bottom due to the shear of the wall, which also leads to many inner plastic zones, (2) interface between the slide surface and the water. As time goes on, the inner plastic zone gets larger, which is a conjunct result of the slide slowdown and the slide getting thinner.

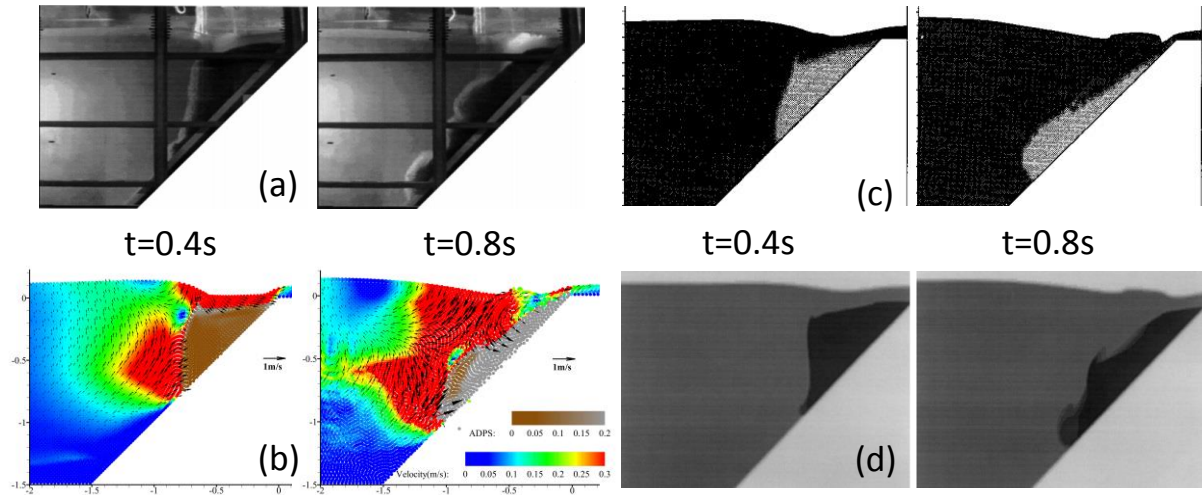


Figure 3. Simulated underwater landslide evolution against experimental data and previous numerical studies

Previous studies on the same problem, which are carried out by Rzedkiewicz et al. (1997) [1] and Mariotti et al. (1999) [6] respectively, are also presented (Figure 3c,d). It should be noted that although these models could all reproduce the main features in the experiments, the parameters used in their studies are very different. How to choose suitable values of parameters is one of the difficulties when using non-Newtonian fluid models. Besides, most of non-Newtonian fluid based models could not represent the shear band in the landslide body, not even the initial failure prediction.

Discussion

Due to the mesh free characteristics, this model do not need mesh and remesh, and is robust enough in very large deformation situation which is not easy to achieve in traditional FEM methods. And because the SPH method is a mesoscale model, parameters in this method is easy to obtained. Comparing with previous studies using non-Newtonian fluid models to describe soil deformation, all parameters in our model have their physical meaning in soil mechanics and can be obtained from conventional soil mechanics experiments. Besides, as we use the elasto-plastic-viscous constitutive law and Drucker-Prager yield model of soil, the deformation of the soil is better represented than it of non-Newton models.

In Fig. 3b, a different shape of the landslide leading edge can also been seen between the experiment and simulation. That is because the velocity of water phase is large and the confining pressure of soil grain is weak at the leading edge of the landslide, which leads to rolling up of the grains in the experiments, while the proposed model cannot reproduce this mechanism properly, which results a smaller thickness. However, dense fluid as these rolling up grains are, they will have little influence on neither internal stress of soil nor the leading wave.

Conclusions

The post-failure evolution of underwater landslides is numerically studied based on a soil-water interfacial coupled smoothed particle hydrodynamics method. The elasto-plastic-viscous model with Dracker-Prager plastic yield rule instead of traditional non-Newtonian model is used for soil deformation simulation and good agreement between simulated results and experiment are obtained. Simulation results show that the landslide body experiences strong deformation during the impact process.

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