Application of Smoothed Particle Hydrodynamics (SPH) for the Simulation of Flow-like Landslides on 3D Terrains

Binghui Cui (✉ bhcui19@hhu.edu.cn)

Hohai University <https://orcid.org/0000-0001-5782-0083>

Liaojun Zhang

Hohai University

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Application of smoothed particle hydrodynamics (SPH) for the simulation of flow-like landslides on 3D terrains

Cui Binghui¹, Zhang Liaojun²

¹ College of Civil and Transportation Engineering, Hohai University, Nanjing, 210000, China,

² College of Water Conservancy and Hydropower Engineering, Hohai University, Nanjing, 210000, China

Correspondence to: Cui Binghui / bhcu19@hhu.edu.cn

Abstract: Flow-type landslide is one type of landslide that generally exhibits characteristics of high flow velocities, long jump distances, and poor predictability. Simulation of it facilitates propagation analysis and provides solutions for risk assessment and mitigation design. The smoothed particle hydrodynamics (SPH) method has been successfully applied to the simulation of two-dimensional (2D) and three-dimensional (3D) flow-like landslides. However, the influence of boundary resistance on the whole process of landslide failure is rarely discussed. In this study, a boundary algorithm considering the friction is proposed, and integrated into the boundary condition of the SPH method, and its accuracy is verified. Moreover, the Navier-Stokes equation combined with the non-Newtonian fluid rheology model was utilized to solve the dynamic behavior of the flow-like landslide. To verify its performance, the Shuicheng landslide event, which occurred in Guizhou, China, was taken as a case study. In the 2D simulation, a sensitivity analysis was conducted, and the results showed that the shearing strength parameters have more influence on the computation accuracy in comparison with the coefficient of viscosity. Afterwards, the dynamic characteristics of the landslide, such as the velocity and the impact area, were analyzed in the 3D simulation. The simulation results are in good agreement with the field investigations. The simulation results demonstrate that the SPH method performs well in reproducing the landslide process, and facilitates the analysis of landslide characteristics as well as the affected areas, which provides a scientific basis for conducting the risk assessment and disaster mitigation design.

Keywords: Flow-like landslides, Smoothed particle hydrodynamics, Non-Newtonian fluid, Boundary treatment

1. Introduction

The occurrence of landslides is usually introduced by earthquakes or heavy rainfall, and are always accompanied by a large number of casualties and extensive damage (Cascini et al. 2012). According to the classification of landslides, there is a term "flow-like landslides", which has the characteristics of fast flow velocity and long run-out distance, that causes severe damage (Mcdougall and Hungr 2004; Huang et al. 2012a; Pastor et al. 2014). Therefore, great attention should be paid to these flow-like landslides to study the flow mechanism and the sliding characteristics. Due to the vast scale, unpredictability, short duration, and destructive character of landslide disasters, it is quite difficult and dangerous to record the process in real time. Numerical methods can simulate the flow behavior of such landslides, and can also be applied

to the investigation and evaluation of landslides. Most numerical studies on the landslides are based on solid mechanics analysis methods, such as the limit equilibrium, finite element method (FEM) (Chatterjee and Krishna 2018) and the fracture mechanics method (Zhang 2020). These methods focus on the slope stability analysis, which analyzes the mechanism of landslide damage from the stress-strain perspective. However, these methods are not able to simulate the large deformation state of the landslide, and thus can not reproduce the whole landslide process.

For physical experiments, it is a very effective and straightforward way of observing the landslide characteristics. However, large-scale landslide or debris flow experiments are very expensive and time-consuming. Recently, numerical simulations based on various numerical methods have been widely employed in the simulation of landslides. The discrete element method (DEM) is a feasible method for simulating landslides (Assefa et al. 2017; Meng et al. 2018; Jiang et al. 2020). DEM treats this geotechnical material as a collection of rigid particles governed by Newton's laws of motion. The interactions between particles are represented through appropriate force-displacement relationships that relate to the overlap and contact forces that can occur between particles. However, sufficiently small time steps are needed to avoid the numerical instability, leading to high costs when simulating the problems containing a large number of elements. To reduce the computational effort, the grain size in a typical DEM simulation is typically significantly less than that in a real problem. Another viable approach is discontinuous deformation analysis (DDA) (Chen et al. 2011; Chen and Wu 2018). Since DDA was proposed, it has undergone extensive modifications and enhancements to make it more suitable for a wide range of real engineering challenges (Zhang et al. 2015; Do and Wu 2020; Wang et al. 2021). However, the characterization of fluid flow still needs further improvement (Wang et al. 2019).

Among the recent advanced numerical methods, SPH is a 'purely' mesh-free method, a completely Lagrangian method in which the particles carry field variables, (such as mass, pressure, energy, etc.) and move with material velocity (Liu and Liu 2010). Since it was first introduced in 1977 to solve the astrophysical problems in three-dimensional open space (Gingold RA 1977; Lucy 1977), it has been widely used in different fields due to its meshless and Lagrangian nature. This method provides better robustness and reliability in solving large deformation simulations, owing to the absence of computational grids or meshes. Therefore, SPH is more suitable for the simulation of flow-like landslides. The SPH still has some inherent flaws, such as the tensile instability, absence of consistency or completeness of interpolation, zero-energy mode, and treatment of boundary conditions, etc. (Ye et al. 2019). With the continuous improvement of the SPH method, the method has been successfully applied to geological hazards (Mcdougall and Hungr 2004; Cascini et al. 2013, 2014; Pastor et al. 2014). Many literatures (Huang et al. 2012b, 2013; Huang and Dai 2014) reported the successful simulation of flow-type landslides as non-Newtonian fluids using the SPH method in combination with the Bingham constitutive model. Most of the existing SHP simulations are based on two-dimensional analysis, which cannot reflect the diffusion and lateral shrinkage, which are different from practical applications. Moreover, the SPH method has recently become more popular, due to the remarkable progress in accuracy, such as the incompressible SPH (Shao and Lo 2003), corrective smoothed particle method (CSPM), and Delta-SPH (Marrone et al. 2011).

Boundary treatment has been the main focus and difficulty of the SPH method, which affects the accuracy and precision of the calculation. Many different approaches have been proposed in the literature to enforce the solid boundary conditions to prevent the particle penetration (Crespo et al. 2007; Tafuni et al. 2018; Negi et al. 2020). The proposal of a generalized wall boundary condition is an alternative to the dynamic boundary conditions, which can be applied in the complex geometries. However, the current simulation of non-Newtonian fluids lacks the treatment of fluid-solid boundaries (Dai et al. 2017). The literature suggested that the application of free-slip boundary conditions to treat the fluid-solid boundary will make the non-Newtonian fluid unable to obtain resistance from the solid wall boundary in the simulation, thus making the simulation and experiment inconsistent (Cao et al. 2019).

In this study, a boundary treatment method is proposed that considers the friction based on the SPH method. The boundary particle viscous force term is obtained by interpolating the values of the fluid particles near the boundary. In addition, the boundary treatment is verified by comparing the simulation results to the experimental data. The Cross model was employed in the SPH method to simulate the landslides. The rheological parameters were derived from the Bingham model and the Mohr-Coulomb criterion. As a case study, the effectiveness and stability of the application were verified by reproducing the Shuicheng flow-like landslide event in both 2D and 3D that occurred on 23 July 2019, in Guizhou Province, China. The simulation results were compared to the field survey data, showing that the SPH model can provide an accurate analysis of the kinetic characteristics of flow-like landslides, including the flow path, movement velocity, runout distance and deposition.

2. SPH method

2.1 Concepts of SPH

For the SPH method, the entire domain is represented as a set of randomly distributed particles with no connection between them. Two main steps are required to obtain the fluid governing equations in SPH form, namely, the kernel approximation and the particle approximation. Firstly, approximation of the field function and its derivative are derived from an integral representation method by using a smoothing kernel function. Secondly, these approximations are replaced by the sum of all neighboring particles in the support domain. It is the kernel approximation and particle discretization that make the SPH method work well for free surface flows and large deformations (Liu and Liu 2010; Violeau and Rogers 2016).

The integral representation of a function $f(\mathbf{x})$ may be given as the following kernel approximation using the smoothing technique:

$$f(\mathbf{x}) \cong \int_{\Omega} f(\mathbf{x}') W(\mathbf{x} - \mathbf{x}', h) d\mathbf{x}' \quad (1)$$

where $f(\mathbf{x})$ is a field function of the three-dimensional position vector $\mathbf{x}$, and $W(\mathbf{x} - \mathbf{x}', h)$ is the smooth function. The smoothing length h that determines support domain Ω . The discrete form of a function at particle i can eventually be described as:

$$f(\mathbf{x}_i) = \sum_{j=1}^N m_j \frac{f(\mathbf{x}_j)}{\rho_j} W_{ij} \quad (2)$$

where m_j and ρ_j are the mass and density of particle j , respectively, and $W_{ij}=W(\mathbf{x}_i-\mathbf{x}_j, h)$ indicates the smoothing function. In the same manner, the particle approximate form for the spatial derivative of the function can be formulated as:

$$\frac{df(\mathbf{x}_i)}{d\mathbf{x}} = -\sum_{j=1}^N m_j \frac{f(\mathbf{x}_j)}{\rho_j} \frac{\partial W}{\partial \mathbf{x}_i} \quad (3)$$

There are several kernel functions that are widely utilized. Typically, higher-order kernel functions often enhance the computing accuracy, and substantial time is required. The cubic spline kernel, which belongs to the B-spline family, is one of the kernels that is commonly employed in SPH method (Liu and Liu 2010) and is given by:

$$W(\mathbf{x}-\mathbf{x}', h) = \alpha_d \times \begin{cases} \frac{2}{3} - q^2 + \frac{1}{2} q^3, 0 \leq q < 1 \\ \frac{1}{6} (2-q)^3, 1 \leq q < 2 \\ 0, q \geq 2 \end{cases} \quad (4)$$

where $q = \frac{|\mathbf{x}-\mathbf{x}'|}{h}$ and $\alpha_d = \frac{15}{7\pi h^2}$ in 2D and $\alpha_d = \frac{3}{2\pi h^3}$ in 3D, respectively. For hydrodynamics of fluids represented in the Lagrangian formulation, the SPH formulations of Navier-Stokes equations can be written as follows:

$$\frac{d\rho_i}{dt} = \sum_{j=1}^N m_j \mathbf{v}_{ij} \frac{\partial W_{ij}}{\partial \mathbf{x}_i} \quad (5)$$

$$\frac{d\mathbf{v}_i}{dt} = \sum_{j=1}^N m_j \left(\frac{\boldsymbol{\sigma}_i}{\rho_i^2} + \frac{\boldsymbol{\sigma}_j}{\rho_j^2} \right) \frac{\partial W_{ij}}{\partial \mathbf{x}_i} + \mathbf{g} \quad (6)$$

$\mathbf{v}_{ij} = (\mathbf{v}_i - \mathbf{v}_j)$ indicates the velocity difference between particle i and particle j ; $\boldsymbol{\sigma}$ represents the total stress tensor and $\mathbf{g}$ is the gravity acceleration, respectively. It is assumed that the temperature is constant throughout the simulation, so the energy equation is not presented.

Due to the density approximation, the pressure field in the SPH formulation for weakly compressible fluids generally exhibits instability and numerical noise. Particularly, in the present case, the noise of the pressure field may be critical. In this study, the delta-SPH method (Marrone et al. 2011) was adopted, which implemented by adding a diffusive term in the continuity Eq.(5) and, can be written as:

$$\frac{d\rho_i}{dt} = \sum_{j=1}^N m_j \mathbf{v}_{ij} \frac{\partial W_{ij}}{\partial \mathbf{x}_i} + \xi h c_0 \sum_{j=1}^N \psi_{ij} \frac{m_j}{\rho_j} \frac{\partial W_{ij}}{\partial \mathbf{x}_i} \quad (7)$$

where ξ is the diffusive coefficient, which is usually adopted as 0.1; c_0 is the speed of sound at reference density; and ψ_{ij} is written as:

$$\psi_{ij} = 2 \left(\frac{\rho_j}{\rho_i} - 1 \right) \frac{(\mathbf{x}_i - \mathbf{x}_j)}{|\mathbf{x}_i - \mathbf{x}_j|^2 + \varepsilon_h h^2} \quad (8)$$

where ε_h is a small constant and is usually adopted as 0.01.

Regarding the momentum Eq. (6), the total stress tensor σ can be written as the summation of an isotropic component pressure p and a viscous shear stress component τ . To remove the numerical oscillations, the Monaghan type artificial viscosity Π_{ij} was adopted in this study, which is most widely used in the current SPH simulation. After considering the artificial viscosity, the momentum equation can be written as:

$$\frac{dv_i}{dt} = -\sum_{j=1}^N m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} + \Pi_{ij} \right) \frac{\partial W_{ij}}{\partial \mathbf{x}_i} + \sum_{j=1}^N m_j \left(\frac{\tau_i}{\rho_i^2} + \frac{\tau_j}{\rho_j^2} \right) \frac{\partial W_{ij}}{\partial \mathbf{x}_i} + \mathbf{g} \quad (9)$$

$$\Pi_{ij} = \begin{cases} \frac{-\alpha_{\Pi} \bar{c}_{ij} \phi_{ij} + \beta_{\Pi} \phi_{ij}^2}{\bar{\rho}_{ij}}, & \mathbf{v}_{ij} \cdot \mathbf{x}_{ij} < 0 \\ 0, & \mathbf{v}_{ij} \cdot \mathbf{x}_{ij} > 0 \end{cases} \quad (10)$$

where α_{Π} and β_{Π} are two constants and are commonly set as 0.1 and 0.01, respectively; Detailed parameter definitions can be found in reference (Monaghan 1992).

In this work, the temperature of landslides is considered as a constant. Therefore, the energy equation is not considered. In the typical SPH method for resolving the compressible flows, the particle motion is governed by the pressure gradient, whereas the particle pressure is determined using an appropriate Equation of State (EoS).

$$p_i = \frac{c_0^2 \rho_0}{\gamma} \left[\left(\frac{\rho_i}{\rho_0} \right)^{\gamma} - 1 \right] \quad (11)$$

where γ is commonly set to be 7.0; c_0 is the speed of sound and is commonly set at least 10 times the maximum fluid velocity for the sake of keeping the density fluctuation within 1% which can be calculated by $\beta (gh_{\max})^{1/2}$. β is a constant and is set as 10 in this study.

2.2 Rheological model

PySPH is an open-source framework for the simulation of the SPH method (Ramachandran et al. 2019). The original PySPH code (version 1.0b1) is able to handle with the free-surface flows, but it is incapable of dealing with non-Newtonian flows. A relevant constitutive model should be developed in the original code to allow for the landslide simulation. In Newtonian fluid dynamics, the shear stress of the fluid can be expressed by the following equation:

$$\tau = \mu \dot{\gamma}^n + \tau_y \quad (12)$$

where $\dot{\gamma}$ is the shear strain rate. The Newtonian fluid is represented by Eq. (12), when $n=1$ and $\tau_y=0$. For a Newtonian fluid, μ is the dynamic viscosity that is given as a constant. The Bingham flow model, as a typical non-Newtonian fluids, can describe the relationship between the shear strain rate and the shear stress of soil (Hadush et al. 2000). When the shear stress τ is greater than the yield strength τ_y , the soil begins to deform. For non-Newtonian fluids, the dynamic viscosity depends on the shear rate or the shear rate history. The relation between a non-Newtonian fluid's shear stress tensor and shear rate tensor can be expressed as:

$$\tau = \mu_{\text{eff}} \dot{\epsilon} \quad (13)$$

181 where μ_{eff} is the effective viscosity that is changed over time. The effective viscosity of the
 182 Bingham model can be formulated as:

$$183 \quad \mu_{\text{eff}} = \mu_B + \frac{\tau_y}{\dot{\gamma}} \quad (14)$$

184 where μ_B is the Bingham viscosity and τ_y is the yield stress, respectively.

185 Assuming that under the condition of shear rate, $\dot{\gamma} \rightarrow 0$, μ_{eff} in Bingham model
 186 approaches an infinite value, therefore, the direct application is not available. To solve this
 187 problem, existing studies employed a variety of strategies to avoid numerical divergence, i.e.,
 188 the simple regularization (Frigaard and Nouar 2005) and the threshold regularization (Laigle et
 189 al. 2007). In this study, the general Cross model (Barnes et al. 1989) was chosen to characterize
 190 the non-Newtonian behavior of flow-type landslides.

$$191 \quad \mu_{\text{eff}} = \frac{\mu_0 + (K\dot{\gamma})^m \mu_\infty}{1 + (K\dot{\gamma})^m} \quad (15)$$

192 where μ_0 and μ_∞ represent the fluid's viscosity at extremely low and high shear rates,
 193 respectively; K and m are the constant parameters of the Cross model. For the sake of simplicity,
 194 the methodology in which these values are derived by incorporating the more commonly
 195 utilized Bingham fluid parameters was adopted (Shao and Lo 2003). Assuming $m=1$ in Eq.
 196 (15), the effective viscosity in the Cross model can be formulated as:

$$197 \quad \mu_{\text{eff}} = \frac{\mu_0 + K\dot{\gamma}\mu_\infty}{1 + K\dot{\gamma}} \quad (16)$$

198 Typically, $K\dot{\gamma} \gg 1$, by Eq. (14) with Eq. (16), the remaining two parameters in the Cross model
 199 can be given as follows:

$$200 \quad \mu_\infty = \mu_B \quad (17)$$

$$201 \quad K = \frac{\mu_0}{\tau_y} \quad (18)$$

202 The Mohr-Coulomb yield criterion, which is adopted to describe the soil yielding process,
 203 is introduced into Eq.(12) (Huang et al. 2012a), which can be written as :

$$204 \quad \tau = \mu\dot{\gamma}^n + c + \sigma \tan \varphi \quad (19)$$

205 where σ is the pressure in this status. Related literature (Hammad and Vradis 1994) pointed out
 206 that the numerical solution's accuracy is satisfactory as the viscosity at a low shear rate is 1000
 207 times greater than that at a high shear rate.

$$208 \quad \mu_0 = 1000\mu_\infty \quad (20)$$

Fig. 1 Effective viscosity against shear rate of different rheological model for parameters ($\mu_b = 20 \text{ Pa} \cdot \text{s}$, $\tau_0 = 100 \text{ Pa} \cdot \text{s}$)

Notice that the advantage of the Cross model over the Bingham model is that the effective viscosity is a continuous variable, and the numerical instability is avoided, as shown in Fig. 1.

2.3 Boundary condition

The boundary treatment has been a main challenge in SPH simulation and affects the calculation accuracy as well as the efficiency. It is vital to select an adequate boundary condition that represents the effect of solid boundary in order to closely describe the dynamic mechanism of landslides, as shown in Fig. 2.

A simple and convenient boundary algorithm was proposed that can consider the boundary friction. In this work, two types of boundary conditions need to be set. Firstly, when a particle approaches to a solid boundary, the kernel function will be truncated, and an error in the solution result will occur. To address this issue, a generalized wall boundary condition by Adami (Adami et al. 2012) (see Eq. (23)), was introduced. By extrapolating from the neighboring fluid particles, the pressure on the solid boundary is obtained as:

$$P_i = \frac{\sum_j (P_j + (\mathbf{g}_j \cdot \mathbf{r}_{ij}) \rho_j) W_{ij}}{\sum_j W_{ij}} \quad (21)$$

Secondly, the discrete particles of landslides may slip at the boundary and thus suffer from the slippage resistance (see Eq. (24)). Referring to the concept of pressure interpolation on the solid boundary, the value of the viscosity force on the solid boundary was given by:

$$\tau_i = \frac{\sum_j \tau_j W_{ij}}{\sum_j W_{ij}} \quad (22)$$

$$\frac{dv_i^p}{dt} = - \underbrace{\sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_j}{\rho_j^2} \right) \frac{\partial W}{\partial x_i}}_{\frac{dv_i}{dt} \leftarrow \text{fluid}} - \underbrace{\sum_j m_j \left(\frac{p_i}{\rho_i^2} + \frac{p_b}{\rho_b^2} \right) \frac{\partial W}{\partial x_i}}_{\frac{dv_i}{dt} \leftarrow \text{boundary}} \quad (23)$$

$$\frac{dv_i^r}{dt} = \underbrace{\sum_j m_j \left(\frac{\tau_i}{\rho_i^2} + \frac{\tau_j}{\rho_j^2} \right) \frac{\partial W}{\partial x_i}}_{\frac{dv_i}{dt} \leftarrow \text{fluid}} + \underbrace{\sum_k m_k \left(\frac{\tau_i}{\rho_i^2} + \frac{\tau_b}{\rho_b^2} \right) \frac{\partial W}{\partial x_i}}_{\frac{dv_i}{dt} \leftarrow \text{boundary}} \quad (24)$$

Through the above two steps, the no-slip boundary conditions considering friction on the solid boundary was successfully set. When calculating the viscous forces on the boundary, both the dynamic viscosity coefficient can be obtained by interpolation from the fluid, or a fixed viscosity coefficient can be set.

Fig. 2 Illustration of the boundary condition algorithm

2.4 Time integration schemes

Prediction-correction algorithm was adopted to execute the time integration. For continuity equations and momentum equations of the form, all the values of time-variant quantities are predicted at the time step $n+1$, based on the time step $n+1/2$, as follows:

$$\rho_i^{n+\frac{1}{2}} = \rho_i^n + \frac{1}{2} \Delta t \frac{d\rho_i^n}{dt}, \quad v_i^{n+\frac{1}{2}} = v_i^n + \frac{1}{2} \Delta t \frac{dv_i^n}{dt} \quad (25)$$

Afterwards, these values are updated at another half time step:

$$\rho_i^{n+1} = \rho_i^{n+\frac{1}{2}} + \frac{1}{2} \Delta t \frac{d\rho_i^{n+\frac{1}{2}}}{dt}, \quad v_i^{n+1} = v_i^{n+\frac{1}{2}} + \frac{1}{2} \Delta t \frac{dv_i^{n+\frac{1}{2}}}{dt} \quad (26)$$

At the end of the time step, the values are calculated as follows:

$$\rho_i^{n+1} = 2\rho_i^{n+\frac{1}{2}} - \rho_i^n, \quad v_i^{n+1} = 2v_i^{n+\frac{1}{2}} - v_i^n \quad (27)$$

The selection of the magnitude of time step Δt is limited due to the stability reasons based on several criteria: the Courant Friedrichs Lewy (CFL) condition, the force terms, and the viscous

diffusion terms, as follows:

$$\Delta t = \min \left(0.25 \frac{h}{c_{\max} + |\mathbf{v}_{\max}|}, 0.125 \frac{h^2}{\nu}, 0.25 \left(\frac{h}{|\mathbf{g}|} \right)^{1/2} \right) \quad (28)$$

3. Verification of the SPH model

In this section, the granular flow model test conducted by Cao et.al. (Cao and Li 2017) was simulated using the SPH model considering friction boundary to verify its accuracy. The vertical section of L-box has a capacity of 2.5 L. The sliding door was lifted up quickly in 2-3 seconds. After the door was opened, the flowing distances of the mortar sample were recorded with a video camera at a certain time interval. One of the cases was chosen for the simulation, and the parameters are given in Table 1.

Table 1 The input parameters of numerical simulations

Parameters	Notation	Value
Density	$\rho(\text{kg/m}^3)$	2150
Bingham viscosity	$\mu_B(\text{Pa} \cdot \text{s})$	560
yield stress	$\tau_0(\text{Pa})$	379
Boundary viscosity	$\mu_s(\text{Pa})$	40
Particle distance	$Dp(\text{m})$	1.5
No. of fluid particles	Npf	1071
No. of boundary particles	Npb	654
Simulation duration	t(s)	6.5

The simulation process is presented in Fig. 3. After the simulation begins, the fresh mortar column collapses under gravity and moves along the bottom of the box. Due to the boundary resistance and its viscosity, the granular flow stopped flowing at the time of 6 s. Moreover, the evolution of the collapsed fresh mortars front before stopped was quantitatively studied and compared with the experimental data. Comparing the simulation results with the test data (Fig. 3), the peak distance and residual deformation of the flow are well captured by the SPH simulation. Fig. 4 shows the numerical and experimental results of the change in L-flow distance over time. To clarify the effect of slippage resistance, the numerical results without considering the slippage resistance are also shown in Fig. 4. The numerical results are not in good agreement with the experimental results when slippage resistance was not considered. This is because that the use of free-slip boundary conditions will make the non-Newtonian fluid unable to obtain sufficient resistance and reaction force from the solid boundary during the process. This section shows that the proposed boundary treatment can simulate a fluid-solid boundary with friction effectively.

Fig. 3 the simulation process and the final shape of L-flow simulation

Fig. 4 Comparison of the numerical and experimental results of L-flow test. (a and b represent the L-flow distance and velocity changing overtime, respectively)

4. Case study

4.1 Geological Setting and flow-like landslides Features

The Shuicheng flow-like landslide event was triggered by intense rainfall in July 2019 (Fig. 5 a). A total of three heavy rainfall events occurred in the week before the occurrence of landslides, with a cumulative rainfall of 288.9 mm. Under the influence of continuous heavy rainfall, the landslide begun to lose stability and rapidly slid along the slope at high speed. After roughly 700 meters of landslide movement, two diversions were formed after hitting a small ridge and subsequently impacting and burying the residential buildings on the lower part of the slope. The mass flow of landslide spreads along the slopes for about 1490 m and was deposited in the gully depressions. Due to the suddenness of the landslide and the lack of protective measures such as blocking, the disaster destroyed 21 houses and 43 people were killed.

The Guizhou Provincial Geological Disaster Emergency Technical Guidance Center immediately carried out the field investigations following the occurrence of landslide. The primary characteristics of the flow-like landslides are depicted in Fig. 5b as well as a typical

cross-section of the Shuicheng gully in Fig. 5c. According to the field investigations, the entire landslide is approximately 1300 m long, with a large distance of around 460 m between the front and rear edges, and a volume of about $191.2 \times 10^4 \text{ m}^3$. According to Zhou et al (Zhou et al. 2021), the average density of the Shuicheng landslide mass was about 2000 kg/m^3 . Depending on the test results, the angle of internal friction and the cohesion of the flow-like landslide can be set approximately as 30° and 30 kPa, respectively. In the previous simulations, the Bingham model was widely applied to simulate the landslides or debris flows considering a range of dynamic viscosities from 20 to 500 $\text{Pa} \cdot \text{s}$ (Hu et al. 2015). In this work, the empirical physical experimental equation is used to obtain the dynamic viscosities (Komatina and Jovanovic 1997), which is given below:

$$\mu_B = 0.621 \cdot \exp(0.173 \cdot C_v) \quad (29)$$

where C_v is the volume concentration. According to the investigation report, the best-fitted C_v is 44 %, resulting in a dynamic viscosity of 255 $\text{Pa} \cdot \text{s}$.

Fig. 5 The 2019 Shuicheng flow-like landslide event (a) Location of the Shuicheng (b) Scope of the landslide (c) typical cross-section of the Shuicheng gully

4.2 Two-Dimensional Modeling

According to the typical cross-section in Fig. 5c, a two-dimensional SPH model was established to simulate the flow behavior of Shuicheng flow-like landslide. 1318 particles were used to represent the landslide and 2678 particles were used to represent the boundary. The initial velocity of the particles was set to zero. After the slope failure, the landslide flow mass particles start to slide downward under the action of gravity. The proposed boundary treatment method considering the friction were utilized, while the boundary particles remained stationary throughout the entire simulation.

According to the simulation results, the whole process duration was about 90s. Fig. 6 presents the slope configurations at different time points, reflecting the movement of landslides. The particles slipped down from the top of the landslide and then moved along the steep slope by gravity. Finally, these particles reached an equilibrium state and were deposited in the lowlands. The overall performance of the sliding was accelerated motion in the period 0-30 s and decelerated motion after 30 s.

Fig. 6 two-dimensional simulated results for the motion process of Shuicheng landslide

Landslides usually have a long distance, and the measurement and selection of various parameters may vary greatly in different locations. Therefore, it is meaningful to conduct a sensitivity analysis to determine how various rheological parameters affect the simulation results. Table 2 lists the eight calculation cases with different rheological parameters. To explicitly quantify the differences of the sensitivity of different parameters ε_v , was evaluated using the following equation:

$$\varepsilon_v = \left(\frac{\sum_i^N \Delta v_j^2}{\sum_i^N v_1^2} \right)^{1/2} \quad (30)$$

where Δv_j is the velocity difference between case j and case 1, and N=18 represents the number of velocity at an interval of 5 s. The results of all the eight cases are presented in Table 2 and Fig.7, which shows that the internal friction angle has more influence on the computation accuracy in comparison with the cohesion of landslides.

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Table 2 Relative error norm in the velocity

Case	Rheological Parameters of flow-like landslides			Consider boundary	Relative Error Norm
	φ (°)	c(kPa)	dynamic viscosity	friction	
1	30	30	255	True	
2	30	30	255	False	0.4411
3	30	0	255	True	0.1828
4	30	15	255	True	0.1089
5	20	30	255	True	0.2928
6	10	30	255	True	0.6119
7	30	30	155	True	0.0133
8	30	30	55	True	0.0530

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Fig. 7 Velocity–time history curves of different cases

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4.3 Three-Dimensional Modeling

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Since the 2D simulation cannot reflect the diffusion and lateral contraction, 3D simulation on the real complex terrain is necessary. In this section, the 3D terrain is generated from the original topographic map at a scale of 1/2000 and homogenizes the mesh. The previously created mesh is then transformed into a sequence of boundary particle particles. Similarly, the landslide is discretized into a succession of particles each with its own set of properties. In this simulation, the particle distance is set to 7.5 m, resulting in 12825 boundary particles and 7010 fluid particles. The strength parameters adopted in the 3D simulation are the same as in the 2D simulation (Table 3). Based on this model, Shuicheng landslide was numerically simulated in 3D terrain, and the results are shown in Fig. 8. The color of the particles in the figures represents the sliding velocity at various instants.

Table 3 Parameters run in the simulation of the Shuicheng landslide

Parameters	Notation	Value
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Density	$\rho(\text{kg/m}^3)$	2150
dynamic viscosity	$\mu_B(\text{Pa} \cdot \text{s})$	255
Angle of internal friction	$\varphi(^{\circ})$	30
Cohesion	$c(\text{kPa})$	30
Particle distance	$D_p(\text{m})$	1.5
No. of fluid particles	D_{pf}	7010
No. of boundary particles	N_{pb}	12825
Simulation duration	$t(\text{s})$	90

The results suggest that the front flow takes about 28 s to travel nearly 520 m to reach the isolated island. The front flow velocity reaches a maximum with an average velocity of 29.8 m/s. Due to the good stability of the soil near the isolated island, it diverts the debris to the sides and forms a divergence. The diversion of the stable slope protects the lower residential houses and creates an "island of safety". The existence of isolated islands has dramatically slowed down the landslides. Therefore, the front flow remains stable at about 90 s and is deposited in the lowlands. Eventually, the estimated total volume of deposition is $1.1 \times 10^6 \text{ m}^3$, which is less than the field investigation value $1.91 \times 10^6 \text{ m}^3$. The reason might be that the simulation process does not take into account the entrapment process. In addition, the simulated landslide paths and deposited areas matched well with the results of field investigations. The topographic data, in this case, were obtained from the 1/2000 scale topographic map, and it is considered that more accurate topographic data would help to obtain better simulation results.

The displacement and velocity time histories of the landslide front and rear were investigated to gain a better understanding of the landslide characteristics in the present simulation. Fig. 9 depicts the velocity time series of the landslide's front and rear. At around 20 s and around 45.5 s after failure, the flow-like landslide front and rear reach a maximum velocity of 29.2 m/s and 26.5 m/s, respectively. Afterwards, an isolated island was encountered, the landslide diverged and the path was changed, and the speed gradually decreased. After moving for 70 s, the landslide came to a halt and was deposited in a lower area. It should be noted that the changes in velocity at various moments represent the complexity of the 3D terrain. Fig. 10 shows the maximum displacements of the front and rear during the motion were 1099 m and 859 m, respectively, at the time of 90s after failure. Ma et al. (Ma et al. 2020) conducted extensive field investigations and calculated the maximum velocity of 25 m/s^2 , and a landslide duration of 60 s using the empirical equations. Both values turned out to be slightly smaller than the simulated results. Quantitative validation of the landslide simulation based on the field measured data and empirical equations were challenging. The error may be triggered by a combination of natural and artificial reasons, which makes the simulation more challenging. In addition, it can be seen that the flow's pressure field is formed smoothly. Fig. 11 depicts the evolution of the flow-like landslide pressure field over time. As previously stated, delta-SPH successfully corrects pressure field noise, particularly for the high viscosity fluids.

Fig. 8 Snapshots of the Shuicheng landslide motion in different instants

Fig. 9 Velocity time history for front and rear of Shuicheng landslide

Fig. 10 Displacement time history for front and rear of Shuicheng landslide

Fig. 11 Pressure field of the Shuicheng landslide in different instants

The landslide material is discretized into a succession of SPH particles of varying diameters in this model. The greater the number of particles and the narrower the particle spacing, the greater the computing time required. It should be mentioned that, in the current code, the SPH module is accelerated based on Open Multi-Processing (OpenMP). In theory, the higher the number of particles in the SPH, the more accurate the simulation will be, but a balance needs to be reached with the needed calculation time. Fig. 12 depicts the relationship between the program runtime and thread count. The results show that the computational efficiency of the proposed SPH model improves as the number of threads increases. Although the OpenMP code is more computationally efficient than the serial code on the CPU, the computation time consumption is large when more particles exist.

Fig. 12 Relationship between computing time and number of threads in 3D SPH model

5. Conclusions

A rational simulation of flow-like landslide propagation process contributes to hazard analysis and disaster mitigation design. In this study, the Navier-Stokes equation combined with the non-Newtonian fluid rheology model was utilized to investigate the dynamic behavior of the flow-like landslide.

1. A simple and convenient boundary algorithm was proposed that can consider boundary friction. By using the proposed boundary algorithm, the simulation results are in good agreement with the experimental results. Moreover, since this operation is limited to boundary particles, it will not increase the computational overhead.

2. The Shuicheng flow-like landslide, which occurred in Guizhou in 2019, was studied as a case. The parameter sensitivity is analyzed under the 2D model, and the results show the shearing strength parameters has more influence on the computing accuracy in comparison with the coefficient of viscosity.
3. A 3D model of Shuicheng landslide was constructed and computed that corresponded to the site conditions. In terms of the solid volume and deposition area, the computed results are generally consistent with the field investigations. In addition, the characteristics of the front and the rear flow velocity and zone of influence of the flow-like landslide were analyzed, which will help to the mitigation or countermeasure design work and offer evidence for the hazard assessment.
4. The approach provides an effective tool for studying the dynamic behaviors of landslides. However, the current study does not take into account the entrainment process of flow-like landslides. Large-scale practical problems usually require massive particles, and future research should be directed to GPU-accelerated modules.

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