A Coupled Discrete Element and Depth-Averaged Model for Flow-Like Landslide Simulations

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Abstract

Flow-like landslides commonly happen in mountainous areas and may cause economic and human life losses in the impacted areas. Computer modelling has become an effective tool for landslide risk assessment and reduction. Models based on discrete element method (DEM) have been widely used for landslide prediction; however, this method is computationally too demanding for large-scale applications. Depth-averaged models (DAMs) have been widely reported for simulating run-out and deposition of flow-like landslides over large spatial domains due to its relatively higher computational efficiency. To combine the advantages of both types of modelling approaches, this work introduces a novel landslide model developed by coupling a DEM model with DAM for simulation of flow-like landslides, in which the DEM is employed in the landslide initiation area to better simulate the failure mechanism of slope, and the DAM is adopted in the landslide runout and deposition phase, where the landslide has developed into flow-like landslide with fluid-like behaviour. Finally, the new coupled model is validated against an experimental test case. Satisfactory results have been obtained, demonstrating that the coupled model is able to accurately capture the detailed dynamics of flow-like landslides.

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Introduction

Landslide such as debris flow, debris avalanche and rock avalanche are common gravity driven granular flows. The granular material often moves at high velocities and travels for long distances in mountainous regions (Iverson and Ouyang 2015), bearing great damaging power that causes severe casualties and significant economic loss (Wei et al. 2019).

Deterministic numerical methods such as limit equilibrium methods (LEMs), continuum approaches and discrete element methods (DEM) have been widely and successfully used for landslide hazard assessment. LEMs are able to quantify the stability of slopes by calculating a safety factor, which is simple and practical to be applied, however, they suffer from the negligence of soil deformation behaviour and the requirement of many assumptions about inter-slice forces (Conte et al. 2014).

With the improvements of both soil constitutive models and computing efficiency, continuum numerical methods such as finite element method (FEM) have been employed in slope stability analysis to study soil deformation behaviour, but it is not well suited for dealing with large deformation and post-failure movements of soils.

To overcome these issues, some alternative numerical tools have been developed. For example, Cundall and Strack (1979) developed the discrete element method (DEM), which is capable of simulating the post-failure movements of granular assemblies, as well as providing an understanding of the mechanical behaviour of landslide materials from a particle-scale point of view (Zhao et al. 2018), thus has been widely used to simulate landslides. However, this method is computationally too demanding (Mirinavicius et al. 2010), thus frequently limited to small-scale simulation.

Observations, both in laboratory and in nature, show granular flows in the downstream are characterized by negligible velocity along the flow depth (Hutter et al. 1995), and therefore it is appropriate for depth-averaged model

(DAM) to describe granular flow dynamics. DAM provides a good way of assessing landslide run-out as it needs neither a precise knowledge of the mechanical behaviour within the flow nor large amount of computational resources, thus can be applied to real 3D topography (McDougall and Hungr 2004; Mangeney et al. 2000) more easily than fully 3D models. However, DAM has limitations on predicting granular flow behaviour in the region where the material has fully dimensional characteristics of flow dynamics.

Herein we propose a new coupled model to conduct landslide simulation, in which computationally expensive DEM is used only in the landslide initiation region to better simulate the soil failure mechanism, and less time-consuming DAM is adopted in the landslide runout and deposition domain in which the landslide has developed into flow-like landslide with flow characteristics. The significant advantage of the proposed coupled model is that it retains the essential flow characteristics of the granular flow with less computational complexity, which makes it possible to perform more accurate large-scale landslide simulation.

The rest of the paper is organized as follows: Sect. 2 presents the coupled landslide model; the proposed coupled model is then validated by carefully selected test cases in Sect. 3; brief conclusions is finally drawn in Sect. 4.

The Coupled Landslide Model

The coupled landslide is applicable for flow-like landslides, consisting of two main parts, i.e. DEM model and DAM. The DEM model is used in the landslide initiation region to provide spatial description of soil failure mechanics; the DAM is employed in the landslide run-out and deposition zone dominated by convective flow dynamics. During the run-out and deposition phase, the depth of landslide is often much smaller than its horizontal span. As a consequence, the changes of vertical flow velocity are negligible compared with its horizontal velocities.

Discrete Element Method (DEM) Model

For the adopted DEM model, the governing equations for translational motion and rotational motion of particles are given respectively as follows

$$m_i \frac{dV_i}{dt} = m_i g + \sum_{j=1}^{k_i} (F_{c,ij} + F_{d,ij}) \tag{1}$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{k_i} T_i + M_i \tag{2}$$

where t is time; m_i is the mass; V_i is the velocity; g is the gravity acceleration; $F_{c,ij}$ and $F_{d,ij}$ are the contact force and damping force between particle i and j, and these forces are summed over the k_i particles in contact with particle i; ω_i is the angular velocity; I_i is the moment of inertia, given by $I_i = \frac{2}{5} m_i R_i^2$. The inter-particle forces acting at the contact point between particle i and j will also cause particle i to rotate and generate a torque T_i. For a circular particle of radius R_i, T_i is given by $T_i = R_i \times (F_{ct,ij} + F_{dt,ij})$, R_i is a vector from the mass centre of the particle to the contact point. $F_{ct,ij}$ and $F_{dt,ij}$ are respectively tangential force and tangential viscous damping force between two particles. M_i is the inter-particle or particle–wall rolling resistance, which is given by $M_i = M_i^k + M_i^d$ (Ai et al. 2011), M_i^k is the spring torque and M_i^d is the viscous damping torque.

Depth-Averaged Model (DAM)

In the depth-averaged model, the granular material is treated as an incompressible Coulomb-type continuum. After depth integration, the fluid properties such as the viscosity and internal friction are packed into a single parameter characterising the friction between the gravel and the terrain at the landslide base (Savage and Hutter 1989).

The depth-averaged equations adopted in this work are modified by Xia and Liang (2018). The matrix form is written as

$$\frac{\partial q}{\partial t} + \frac{\partial f(q)}{\partial x} = S_b + S_f \tag{3}$$

where the vector terms are given by

$$q = \begin{bmatrix} h \\ uh \end{bmatrix} f(q) = \begin{bmatrix} uh \\ u^2 h + \frac{1}{\varphi^2} \frac{1}{2} g h^2 \end{bmatrix} \tag{4}$$

$$S_b = \begin{bmatrix} 0 \\ -ah \frac{\partial b}{\partial h} + \frac{1}{2} g h^2 \frac{\partial(1/\varphi^2)}{\partial x} \end{bmatrix} \quad S_f = \begin{bmatrix} 0 \\ -\frac{\mu a h u \varphi}{\sqrt{u^2 + \left(u \frac{\partial h}{\partial x}\right)^2}} \end{bmatrix} \tag{5}$$

with $a = \frac{1}{\varphi^2} \left(g + u^2 \frac{\partial^2 b}{\partial x^2}\right)$, in which $\varphi = \left[\left(\frac{\partial b}{\partial x}\right)^2 + 1\right]^{\frac{1}{2}}$, where h is the landslide material depth, b is the bed elevation, u is the x-direction depth-averaged velocity, μ is the friction coefficient. The factor of $\frac{1}{\varphi^2}$ describes the effects of complex topography in a Cartesian coordinate system. $u^2 \frac{\partial^2 b}{\partial x^2}$ is used for representing the effect of centrifugal force.

Boundary Conditions at the Coupling Interface

In the coupled model, the coupling takes place at the interface between the DEM model and DAM by considering conservation of mass, in which the boundary conditions of DAM such as flow discharge q and depth h are acquired from the DEM simulation results. As shown in Fig. 1, the particles may be not perfectly aligned to the interface, thus a boundary area is introduced to identify the flow variables along the interface.

The boundary conditions are written as follows

$$h^{IF}(x = x_{IF}) = h^{DEM}(x = x_{IF}) \qquad (6)$$

$$q^{IF}(x = x_{IF}) = u^{IF}(x = x_{IF})h^{IF}(x = x_{IF}) \qquad (7)$$

where h^{IF} and q^{IF} are the granular depth and discharge in the boundary area recognised as the boundary conditions of DAM; x_{IF} is the interface position; h^{DEM} is gained by averaging the vertical positions of the first three highest particles in the boundary area; u^{IF} is the velocity in the boundary area calculated by considering mass conservation, expressed as

$$u^{IF} = \frac{1}{N}\sum_{i=1}^{N} u_i^{DEM} + \frac{\Delta m}{\rho_{DAM}h^{IF}} \qquad (8)$$

where N is the number of particles in the boundary area; u_i^{DEM} is the velocity of particle i; ρ_{DAM} is the material density in the DAM, deduced as $\rho_{DAM} = \rho_{DEM}(1 - n_p)$, of which ρ_{DEM} is the density of the DEM particle material, n_p is the porosity of the material in the DAM. The term of $\frac{\Delta m}{\rho_{DAM}h^{IF}}$ is to guarantee the mass conservation, in which Δm is presented as $\Delta m = m_t^{DEM} - m_t^{DAM}$. m_t^{DEM} is the actual mass of particles feeding into the DAM region from the DEM region, denoted as $m_t^{DEM} = \sum_{i=1}^{N_0} m_i$, and m_i is the mass of the particle i, expressed as $m_i = \rho_{DEM}\pi R_i^2$, of which R_i is the radius of particle i, N_0 is the number of particles coming
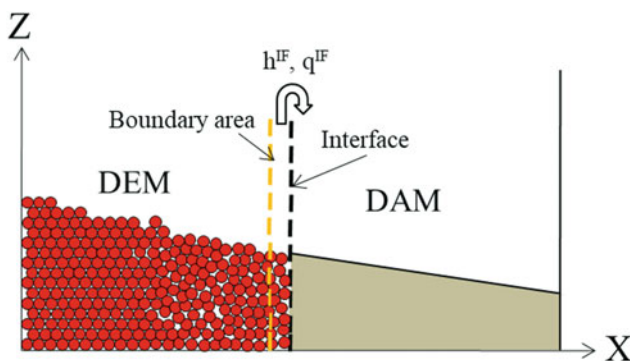
into the DAM in the simulation time t. m_t^{DAM} is the mass of flow calculated by the interface boundary conditions, expressed as

$$m_t^{DAM} = \int_0^t \rho_{DAM} h^{IF} u^{IF} \qquad (9)$$

where t is the simulation time. If $\Delta m > 0$, it means that the mass of material feeding into the DAM region is larger than the mass calculated through boundary condition in DAM, so Δm is added to m^{DAM} by increasing the velocity u^{IF} at the next time step; if $\Delta m < 0$, it means that the mass calculated by boundary conditions in DAM is larger than the actual mass coming into the DAM region, so Δm is deducted from m^{DAM} by decreasing the velocity u^{IF} at the next time step.

Model Validation and Result

In this section, and coupled model presented in the previous section are validated against an experimental test case.

Experiment of Dam-Break Granular Column Collapse

Lajeunesse et al. (2005) conducted a series of experiments on granular material collapse. In their experiments, as illustrated in Fig. 2, particles are inserted randomly into the reservoir to form a loosely packed column. The granular pile is released by quick lifting of the sliding gate, and then granular particles spread along the horizontal plane until came to rest. The angle of response is 13.93°. The reason for choosing this experiment is that by analysing and comparing the process of granular material collapse from the experiment and different models, the added value of the coupled model for simulating granular collapse can be demonstrated.

As presented in Fig. 3, the interface between the DEM and DAM is set at the position x where $x/L_i = 2.45$. The material profiles with non-dimensionalised flow height (h/L_i) and length (x/L_i) of different models are measured at different times proportional to characteristic time τ_c. The characteristic time τ_c is expressed as $\tau_c = \sqrt{\frac{H_i}{g}}$, corresponding to the free-fall time of the granular material. In the measurement of granular profile in the DEM, the particles separated from the main portion of granular material are not considered.

Figure 3 shows that the simulation results of the DEM and coupled model are generally consistent with the experimental results, which highlights that both the coupled model and the DEM can provide accurate prediction of the run-out distance and run-out durations, as well as

Fig. 1 Schematic of boundary conditions at the interface between the DEM and the DAM
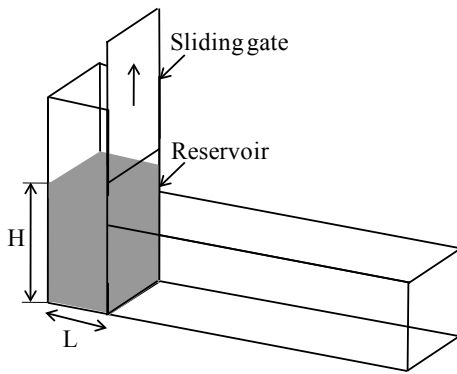
Fig. 2 Schematic of dam-break like granular material collapse

deposit morphology. In contrast, the material collapse simulated by the DAM only is not in line with the experimental results. The granular material moves more quickly and comes to rest earlier than the other two

models and the experiment. This may be because the DAM neglects the vertical momentum damping at the region of landslide initiation and thus gains bigger horizontal momentum. In addition, the whole simulation takes 200 s in the DEM model, and it is 144 s in the coupled model on the same machine. This indicates that the coupled model saves 28% computing time and is more computationally efficient compared with DEM model. The gain of efficiency is expected to be more substantial for real-world cases, where the DAM constitutes a much larger proportion of the whole domain.

There exists a general trend in Fig. 3 that the DEM results and the coupled model results converges to the experimental observation as time goes on. At the time of $t = \tau_c$ and $t = 2\tau_c$, there is a slight difference between the DEM results, coupled model results and experimental results, which may be caused by the difference in particle packing patterns in the initial settings. Although particles are randomly inserted into the reservoir to finally form a loosely packed granular

Fig. 3 Sequences of scaled profiles of granular collapse interface
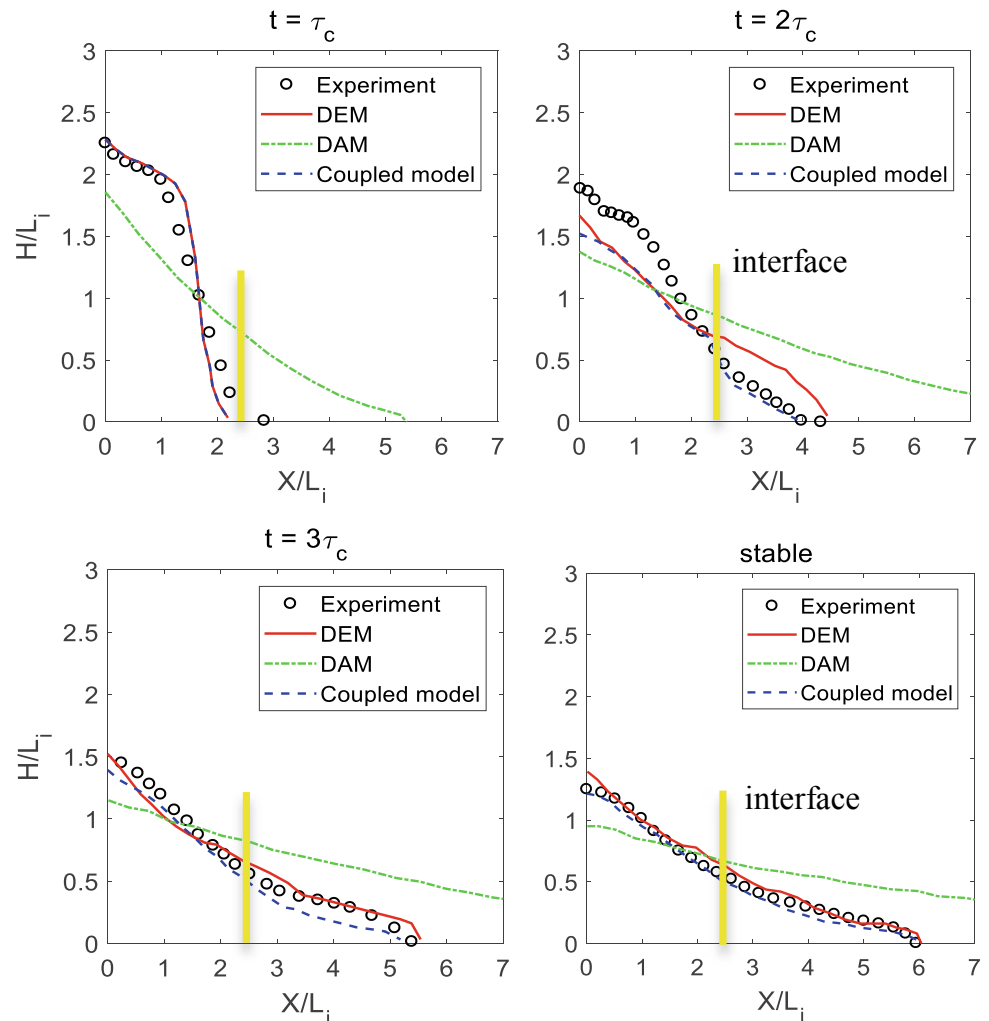
column both in the experiment and DEM, the initial settings of particles are still not identical. As the granular material collapse keeps going, the effect of initial setting of particles on the granular flow dynamics diminishes. As a result, the numerical simulations converge to the experiment as the granular flow further develops.

At $t = 2\tau_c$ and $t = 3\tau_c$, the flow depth predicted by the coupled model is smaller than that by the DEM. This is mainly because in the coupled model, DAM considers flow-like granular materials as continuous matter and therefore the void ratio is minimised as like densely packed material. However, DEM discretize the material as particles and there exists additional void between particles because of collisions between particles when the granular material collapses. The additional void between particles lead to a difference on the flow depth between the DEM and coupled model. After the particle movement come into a steady state, there is little additional void between particles and the granular material profile gained from the DEM and coupled model are consistent.

Conclusion

This paper demonstrates that the newly developed landslide model is a potential alternative, with high efficiency and good predictive capabilities, to conventional methods for the simulation of large-scale landslides. The new landslide model is developed by coupling the DEM model and DAM, in which DEM analyses the failure dynamics of soils in the landslide initiation zone and also provides boundary conditions for the DAM to simulate the overall flow dynamics in the downstream area such as the landslide runout and deposition zone where the predominant advective landslide dynamics have been well developed. This longitudinal coupling strategy reduces the spatial complexity of the landslide simulation and thus significantly increases the computational efficiency.

The experiment of dam-break like granular collapse is employed to validate the coupled model. Satisfactory solution has been obtained, which confirms the simulation capability of the coupled landslide model.

References

Ai J, Chen JF, Michael Rotter J, Ooi JY (2011) Assessment of rolling resistance models in discrete element simulations. Powder Technol 206(3):269–282

Conte E, Donato A, Troncone A (2014) A finite element approach for the analysis of active slow-moving landslides. Landslides 11 (4):723–731

Cundall PA, Strack ODL (1979) A Discrete numerical model for granular assemblies. Geotechnique 29(1):47–65

Hutter K, Koch T, Pluüss C, Savage SB (1995) The Dynamics of avalanches of granular materials from initiation to runout. Part II. Experiments. Acta Mech 109(1–4):127–165

Iverson RM, Ouyang C (2015) Entrainment of bed material by earth-surface mass flows: review and reformulation of depth-integrated theory. Rev Geophys 53:27–58

Lajeunesse E, Monnier JB, Homsy GM (2005) Granular slumping on a horizontal surface. Phys Fluids 17(10)

Mangeney A, Heinrich P, Roche R (2000) Analytical solution for testing debris avalanche numerical models. Pure Appl Geophys 157 (6–8):1081–1096

McDougall S, Hungr O (2004) A model for the analysis of rapid landslide motion across three-dimensional terrain. Can Geotech J 41 (6):1084–1097

Mirinavicius A, Markauskas D, Kacianauskas R (2010) Computational performance of contact search during dem simulation of hopper filling. In: 10th international conference modern building materials, structures and techniques, June 2014, pp 974–979

Savage SB, Hutter K (1989) The motion of a finite mass of granular material down a rough incline. J Fluid Mech 199(2697):177–215

Wei Z, lei, Qing Lü, Hong yue Sun, and Yue quan Shang. (2019) Estimating the rainfall threshold of a deep-seated landslide by integrating models for predicting the groundwater level and stability analysis of the slope. Eng Geol 253(March):14–26

Xia X, Liang Q (2018) A new depth-averaged model for flow-like landslides over complex terrains with curvatures and steep slopes. Eng Geol 234:174–191

Zhao S, Evans TM, Zhou X (2018) Effects of curvature-related DEM contact model on the macro- and micro-mechanical behaviours of granular soils. Geotechnique 68(12):1085–1098