THREE-DIMENSIONAL SIMULATION OF THE HONGSHIYAN LANDSLIDE WITH THE MATERIAL POINT METHOD

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In mountainous areas of Southwestern China, landslides often take place. They are highly dynamic accompanied with large deformation and are inherently difficult-to-predict due to complicated topography. In this study, a coupling approach of the material point method (MPM) and ArcGIS terrain data is developed for the three-dimensional modelling of landslides. MPM is a continuum-based particle method, which is convenient to implement various boundary conditions and constitutive laws. The real terrain data extracted and pre-processed from ArcGIS software are used to model the foundation boundary and the sliding body. The Hongshiyan landslide, which occurred in August, 2014 in Yunnan Province, China, was chosen for the simulation of its sliding process with the approach proposed in this work.

Keywords: landslide; material point method; ArcGIS; rheological relation

INTRODUCTION

Estimation of the initiation and runout process of a landslide is of great importance in the prevention of natural disasters and reduction of risks to local residents and infrastructures (Xu et al., 2016). Traditional geotechnical research of landslides focused on failure prediction and factor of safety based design, which have difficulties in describing the post-failure behaviors with large deformation (Soga et al., 2016). Considering that the discrete element method (DEM) has limitations to simulate large mass of soil and that the finite element method (FEM) has problems of mesh distortion, meshfree methods within the framework of continuum mechanics (e.g. smoothed particle hydrodynamics (SPH) and MPM) are now being the popular choice for large deformation problems. SPH is a fully Lagrangian method and is widely applied to flow-like landslides, but it exhibits spatial instabilities and consumes time to search for the neighbouring particles (Bandara and Soga, 2015). MPM is a hybrid Eulerian-Lagrangian approach. By incorporating advanced constitutive models of soil or granular materials, it can analyze landslides from the pre-failure stage with small strains to the post-rupture phase involving large deformation (Alonso et al., 2015). Recent works on MPM for slope stability problems include retrogressive and progressive slope failure, slope seismic response (Bhandari et al., 2016), slope failure with weak layers, rainfall-infiltration-induced landslides, interaction between the flow-like landslides and rigid structures and post-failure runout processes of the Wangjiayian landslide (Li et al., 2016). Most landslide simulations using meshfree methods are two-dimensional or depth-averaged, while there are still limited reported cases for modelling real three-dimensional landslides.

MPM can adopt complex boundaries with background mesh, and calculate arbitrary-shaped objects with material points discretization. ArcGIS is an efficient geography tool for spatial data management. Therefore, this paper reports the work of coupling MPM with ArcGIS terrain.
data for modelling the three-dimensional movement of a landslide. The flow process of a landslide is often accompanied by a transitional behavior from solid-like to fluid-like states and this brings difficulties in proposing a unified phenomenological constitutive model. Recently two continuum constitutive models are developed for multi-states granular flows based on the MiDi rheological relations (Dunatunga and Kamrin, 2015, Fei et al., 2016). Although the performance of such models have been verified for simple cases, but they are yet to be applied to real landslide simulations.

This paper is organized as follows: the section of methodology presents the modelling scheme of MPM coupled with ArcGIS terrain data, and the constitutive law of multi-phase granular flows. A simulated example of the Hongshiyan landslide is given in the result section. The findings from the work are summarized in the conclusion section.

METHODOLOGY

Disaggregated landslides can be deemed as granular flows composed of coarse individual particles. Within the continuum mechanics of MPM, they are treated as a continuum body, which is further divided into a set of material points (Fig.1(a1-a4)). Each material point (MP) storing all the physical variables of its representative area, such as mass and momentum, are linked to the background grid nodes (GN). A calculation cycle contains: (b1) mapping MP information to GN, (b2) solving momentum equations on GN and update their positions and kinetics, (b3) mapping updated information of GN back to MP, (b4) updating the positions and kinetics of MP, (b5) resetting deformed grids (Fig.1(b1-b5)). Particle domain of material points is in Lagrangian description allowing an arbitrary movement, while the grid view is in Eulerian description with background mesh actually keeping still after each step (Fig.1(c1-c4)).

The motion of a material point is mainly governed by the balance of momentum

\[ \rho \ddot{v} = \nabla \cdot \sigma + \rho \mathbf{b} \]

where \( \rho \) is the density, \( \dot{v} \) is the acceleration vector, \( \nabla \cdot \sigma \) is the spatial gradient of stress tensor, and \( \mathbf{b} \) is the specific body force. With the shape function \( N_{ip} = N(I_p) \) of grid node \( I \) on material point \( p \), it is solved on the background mesh according to the Newton's second law

\[ \dot{p}_d = f_d^{int} + f_d^{ext} \quad p_d^{t+1} = p_d^t + (f_d^{int} + f_d^{ext}) \Delta t \]

where the the material point quantities (mass \( m_p \), momentum \( p_p \), internal force \( f_d^{int} \) and external force \( f_d^{ext} \) ) are all mapped to the grid nodes

\[ m_p = \sum_{p} m_N N_{ip} \quad p_p = \sum_{p} \rho_p m_p N_{ip} \]

\[ f_d^{int} = -\sum_{p} \rho_p N_{ip} \sigma_{ij} N_{ip} \quad f_d^{ext} = \sum_{p} m_p N_{ip} \mathbf{b}_p + \sum_{p} \mathbf{f}_d^{int} \sigma_d \]

Fig.1 The calculation scheme of MPM

Fig.2 The coupling sketch of MPM and ArcGIS data
The motion of grid nodes leads to the deformation of cells $\Delta x_{ij}^{n+1}$, according to which the constitutive law of material is applied to update the stress of MP. In this paper, the total stress $\sigma$ is divided into two terms, the rate-independent stress $\sigma'(\varepsilon)$ and the rate-dependent kinetic stress $\sigma''(\dot{\varepsilon})$. The former term is calculated by Drucker–Prager elastoplastic model, while the latter one by $\mu(t)$ rheological relation, which emphasizes the energy dissipation nature.

$$ \sigma = \sigma'(\varepsilon) + \sigma''(\dot{\varepsilon}) $$

$$ d\sigma_i^0 = C_{ijkl}(d\varepsilon_{ij} - d\varepsilon_{kl}^0) \quad \sigma'' = -a\dot{\varepsilon}^p \sigma_0 D_t $$

Here, $C_{ijkl}$ is the elastic stiffness tensor, $d\varepsilon_{ij}$ is the total strain increment and $d\varepsilon_{kl}^0$ is the plastic component; $D_t = \frac{\gamma_0 - \delta_0 \dot{\varepsilon}_0 l^3}{\sqrt{2\gamma_0^2 l^3}}$, $\gamma_0 = d\varepsilon_l / dt$ is the shear rate; $I = \frac{\gamma d}{\sqrt{\sigma''/\rho}}$ is the inerial number, $\gamma = \frac{m_0 l^3}{\rho}$, $\sigma''$ is the spheric stress; $a$ and $b$ are experimental parameters of material properties (Dunatunga and Kamrin, 2015, Fei et al., 2016).

As shown in Fig.2, the ArcGIS terrain data downloaded from Geospatial Data Clouds are preprocessed in a format of $M \times N$ square rasters and interpolated into higher resolutions. Where there is no terrain, a null value of -9999 is set. Each raster carries its DEM (digital elevation model) elevation, which can be divided into the height of foundation boundary $H_i (i=1,2...)$ and the relative elevation $\Delta H_i (i=1,2...)$ of the sliding body. To import the special data into MPM, we use a cubic cell in eight nodes in a Cartesian background mesh. The shape function can be written as $N_{vi} = (1+\varepsilon_{vi})(1+\eta_{vi})(1+\zeta_{vi})/8$. The sliding mass of landslide is discretized into material points carrying the position and mass of its representative area. The base boundary is fixed with zero displacement on the grid nodes. Before the runout process, the initial stress is generated using gravity loading by increasing the strength of the sliding body in an elastic constitutive model.

**RESULTS**

The Hongshiyan landslide was triggered by the Ludian earthquake, which took place in Yunnan province, China on August 3, 2014. The avalanche body of about 17.0 million m$^3$ in volume rushed into the Niulan River and formed a dammed lake. The before- and after-earthquake topography data were obtained from on-site geological survey. We chose an area of xyz=1800x1320m as the computational domain with the elevation $z=1000-2000m$.

Firstly, a validation case of granular column collapse was conducted in comparison with the experimental results (Xu et al., 2016) and it exhibited a good match. Then the numerical model of the Hongshiyan landslide was constructed three-dimensionally with 5m resolution. The size of the background cell was 5m and the cell contained four material points initially. The time step was automatically calculated as $\Delta t \approx 4.5 \times 10^{-4} s$, and the total calculation time was 100s. The material parameters of $E=10MPa$, $\nu=0.4$, $\rho=1700kg/m^3$, $\phi=26^\circ$, $c=0kPa$ were the young modulus, the poisson's ratio, the absolute density, the friction angle and the cohesion coefficient, respectively. In Eq. (5), the $\mu(t)$ rheological parameters of $a=25$ and $b=1.0$ were estimated from the maximum speed of granular flows along the inclined slope.

Figure 3 shows the deposit thickness of material points above the initial foundation boundary during the dynamic movement of the Hongshiyan landslide. The simulation was activated at $t=0s$ by gravity driving. The weak soil then began to slide down the slope in an inclination angle of approximate 45$^\circ$, with the velocity increasing rapidly. The avalanche body was disaggregated and collapsed to rush into the Niulan river. During the conversion of gravitational potential energy to kinetic energy, the front of the sliding body reached a
maximum velocity of about 60m/s at $t = 30s$. After that, the velocity began to decrease and the deposit became larger and larger. At about $t = 50s$ the thickness of the deposit peak reached the maximum of 120m, but the soil on the two sides was still creeping along the horizontal channel balanced by the force of friction and the moment of inertia. The simulation lasted about 80s and the final configuration of deposit is shown in Fig. 3, which is very close to the realistic result.

CONCLUSION

This work reports a three-dimensional modelling scheme for landslides. MPM is a suitable continuum method for large deformation problems, and is convenient to implement the boundary conditions of complicated topography. ArcGIS terrain data is pre-processed and used to model the foundation boundary and the avalanche body. Meanwhile by adopting $\mu(I)$ rheological relation, the developed approach shows great potentials to study the mechanics of multiple mechanical phases of disaggregated landslides.

REFERENCES


