Three-dimensional debris mobility modelling coupling smoothed particle hydrodynamics and ArcGIS

Hydrodynamisme de particules lissées en trois dimensions des débris couplage de modélisation de la mobilité et ArcGIS

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ABSTRACT: Landslides from natural hillsides could result in serious consequence to life and property in Hong Kong due to its dense urban development in a hilly terrain combined with high seasonal rainfall. Over the past 35 years, Hong Kong has maintained continual slope safety efforts through a suite of landslide risk management tools to reduce and contain landslide risk within an as low as reasonably practicable level that meets the needs of the public and facilitates safe and sustainable developments. In particular, landslide mobility has been a major area of technical development and its results have been instrumental to overall landslide risk management in Hong Kong. For natural terrain landslides, two-dimensional modelling of landslide motions has been routinely used to assess landslide mobility in natural terrain hazard studies. In this paper, a new three-dimensional modelling module, 3d-DMM, developed using smoothed particle hydrodynamics (SPH) and ArcGIS are introduced. The theory of SPH and the methodology that couples SPH and ArcGIS to simulate natural terrain landslide mobility are explained. Validation of the module is discussed by comparing results of back-analyses of six historical landslides with the available field velocity and runout data to demonstrate that the module results are consistent with the field data/observations.

RÉSUMÉ : Les glissements de terrain des collines naturelles pourraient avoir des conséquences graves pour la vie et les biens à Hong Kong en raison de son développement urbain dense dans un terrain vallonné combiné à de fortes précipitations saisonnières. Au cours des 35 dernières années, Hong Kong a maintenu des efforts constants en matière de sécurité des pentes grâce à une série d'outils de gestion du risque de glissements de terrain pour réduire et contenir les risques de glissements de terrains à un niveau aussi bas que raisonnablement réalisable et répondant aux besoins du public. En particulier, la mobilité des glissements de terrain a été un domaine important de développement technique et ses résultats ont contribué à la gestion globale du risque de glissements de terrain à Hong Kong. Pour les glissements de terrain naturels, la modélisation bidimensionnelle des mouvements de glissements de terrain a été systématiquement utilisée pour évaluer la mobilité des glissements de terrain dans les études de risques naturels. Un nouveau module de modélisation tridimensionnel, 3d-DMM, développé en utilisant l'hydrodynamique des particules lissées (SPH) et ArcGIS sont introduits. La théorie de SPH et la méthodologie qui associe SPH et ArcGIS pour simuler la mobilité des glissements de terrain naturels sont expliquées. La validation du module est discutée en comparant les résultats des analyses de retour de six glissements de terrain historiques avec les données de vitesse de champ et d'évanouissement disponibles pour démontrer que le module produit des résultats cohérents avec les données / observations de terrain.

KEYWORDS: Smoothed Particle Hydrodynamics, natural terrain landslides, back analysis, geographic information system

1 INTRODUCTION

Debris flow is a common form of natural terrain landslides in Hong Kong. Because of its potential of high mobility, even a small-scale debris flow that occurs in a dense urban setting is liable to result in severe consequences. A quality and reliable assessment of landslide risk posed by natural terrain is indispensable to the planning, design, and deployment of cost-effective landslide risk management strategy, thus calling for the development and validation of a numerical tool which is capable of performing forward prediction of landslide mobility in an efficient manner.

Two-dimensional debris mobility modelling code has been developed by the Geotechnical Engineering Office (GEO) in the early 2000's (Kwan and Sun, 2006), and has been routinely used to assess landslide mobility in natural terrain hazard studies in Hong Kong since then. Experience has been gained in relation to the input parameters which should be adopted for assessing landslide mobility in natural terrain hazard studies in Hong Kong, mainly based on the high-quality database of natural terrain landslides in Hong Kong which are developed and managed by the GEO.

With the advance in digital and computer technology, modelling of landslide motions over 3-dimensional terrain is not uncommon. Back in the late 2000s, Kwan and Sun (2007) adopted the Particle-in-Cell (PIC) numerical technique to solve the governing equations to simulate 3-dimensional landslide debris mobility. The PIC numerical technique is similar to the material point method reported by Soga et al (2016).

Another 3-dimensional modelling module that uses Smoothed Particle Hydrodynamics (SPH) introduced by McDougall and Hungr (2004) to simulate debris mobility has recently been developed by the GEO. The SPH model employs the meshless Lagrangian finite difference approach and adopts the Saint-Venant shallow water assumption and the Voellmy rheology to simulate the dynamics of landslide debris under large deformation. Three-dimensional simulations of landslide debris mobility require pre-processing and post-processing of a large amount of three-dimensional spatial data. In order to enhance its efficiency in performing three-dimensional landslide mobility analysis, an additional Geographic Information System (GIS) module has been developed. It provides an improved Graphical User Interface which guides users through defining a problem, solving the problem through SPH modelling and analysing the simulation results on the ArcGIS platform in a seamless manner.

The software package, which comprises the SPH code and the ArcGIS application, is called 3d-DMM, which stands for three-dimensional Debris Mobility Modelling. Following the development of the 3d-DMM, the software package was validated against measured data from the historical natural terrain landslides to ascertain its suitability for application in geotechnical design and risk assessment.

This paper presents the governing equations and numerical scheme of the SPH model, and introduces the ArcGIS application which integrates the SPH and ArcGIS. Findings of the back analysis of the SPH model using historical natural terrain landslides are also presented.

2 INTRODUCTION TO 3D-DMM

2.1 *Governing Equations*

Landslide debris is considered as an equivalent fluid in setting up the equations of motion, thus treating the bulk of the landslide debris as a continuum. The motion of the landslide debris follows the mass and momentum conservations equations with Saint-Venant shallow water assumption. It should be cautioned that 3d-DMM is not suitable to simulate debris dynamics involving an abrupt change in slope gradient. An abrupt change in slope gradient introduces considerable momentum transfer along the normal direction of the channel bed, of which the Saint-Venant shallow water assumption takes as insignificant. The Cartesian coordinate system is adopted with the direction normal to the channel bed as the z-axis. The governing equations of motion are presented below:

Mass Conservation:

$$\frac{\partial h}{\partial t} + h(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}) = E_t \tag{1}$$

Momentum Conservation in x-direction:

$$\rho h \frac{\partial u}{\partial t} = \rho g_x h - k_x \sigma_z \left(\frac{\partial h}{\partial x}\right) - \tau_{xbed} - \rho u E_t \tag{2}$$

Momentum Conservation in y-direction:

$$\rho h \frac{\partial v}{\partial t} = \rho g_y h - k_y \sigma_z \left(\frac{\partial h}{\partial y}\right) - \tau_{ybed} - \rho v E_t \tag{3}$$

where x = the direction of motion
y = the direction perpendicular to the x and z axes
z = the direction normal to the channel base
u = velocity component in the x direction
v = velocity component in the y direction
ρ = debris density
g_x = gravity acceleration in the x direction
g_y = gravity acceleration in the y direction
σ_z = bed-normal earth pressure
h = debris depth
k_x = tangential earth pressure coefficient in the x direction
k_y = tangential earth pressure coefficient in the y direction
τ_{xbed} = basal shear stress in the x direction
τ_{ybed} = basal shear stress in the y direction
E_t = erosion velocity, change of mass due to erosion over unit time

In Equations 2 and 3, the terms on the left-hand side of the momentum equations represent the debris accelerations in the respective directions. The first term on the right-hand side relates to the body force, and the second term represents the internal pressure arising from the effect of the debris depth gradient. The third term (τ_{xbed} and τ_{ybed}) in the momentum conservation equations represents the base friction against the debris motion, which depends on the rheology of the debris. The last term in the momentum conservation equations represents the change of momentum due to entrainment. Ayotte and Hungr (1998) studied 20 landslides and debris flows in Hong Kong. They showed that the Voellmy rheological model (Voellmy, 1955) could produce a reasonable estimate of the basal resistance.

In accordance with the Rankine theory, the tangential earth pressure coefficients (i.e. k_x and k_y shown in Equations 2 and 3 respectively) are limited by the Mohr-Coulomb failure criterion. The minimum and maximum limiting values correspond to the "active" and "passive" states, respectively. The limits of the tangential earth pressure coefficient are calculated using the equations proposed by Savage and Hutter (1989). The SPH model uses the apparent friction angle to calculate the k_x and k_y. A series of sensitivity study of the apparent friction angle has been carried out using the historical natural terrain landslides in Hong Kong which concluded that the computed results were in general not sensitive to the apparent friction angle. This is in agreement with Hungr (1995). The apparent friction angle was taken as 30° in the validation of 3d-DMM discussed in Section 4.

2.2 *Method of SPH*

In SPH, the landslide debris is discretised into a cluster of smoothed particles. Each of the particles in this method has a finite volume (V_i), and bears an influence zone defined by an interpolation kernel (W). Properties such as debris depth and velocity at any location can be estimated by summation of the interplant of particles within the local influence radius. For example, the total debris thickness, h_i, at the position of particle i, is calculated as:

$$h_i = V_i \sum_{j=1}^{n} W(s_{ij}, l) \tag{4}$$

where s_{ij} = distance between particle i and j
l = radius of the influence zone

The interpolating kernel, W, is a function of s_{ij} and l. The variable s_{ij} is the separation distance between the particle i and particle j, which is within the influence zone of the particle i. The radius of the influence zone is l. The summation is undertaken for all particles (i.e. j = 1 to n) within the influence zone. The kernel is represented by the following Gaussian function:

$$W(s_{ij}, l) = \frac{1}{\pi l^2} \exp\left[-\left(\frac{s_{ij}}{l}\right)^2\right] \tag{5}$$

The radius of the influence zone (l) is defined as follows:

$$l = \frac{B}{\sqrt{\dfrac{\sum_{i=1}^{N} \frac{h_i}{V_i}}{N}}} \tag{6}$$

where B = smoothing coefficient
V_i = volume of the smoothed particle i
N = total number of particles used for representing the whole debris mass
s_{ij} = distance between particles i and j
l = radius of the influence zone
h_i = total debris thickness at the position of particle i

With the above kernel function, the debris thickness and depth gradient can be calculated at each particle location. Having calculated debris thickness and depth gradient, acceleration of each of the particles can be obtained based on the momentum conservation equation. A series of sensitivity study of the smoothing coefficient (B) using the historical landslides in Hong Kong has been carried out which concluded that the computed mobility of the debris front was, in general, less sensitive to B when B equal 4 or below. The value of 4 was also the suggested value by McDougall and Hungr (2004) and was chosen in the validation of 3d-DMM discussed in Section 4. The simulation is undertaken in a time-stepping framework with an initial condition that all the particles are at rest. At each time step, the velocities of the particles are updated based on the acceleration calculated via the momentum conservation equations and the particles are displaced to new positions. There are special cases where the influences between smoothed particles located within the influence zone are not reasonable. For example, the kernel function would average the thickness and acceleration of two separate clusters of smoothed particles representing two different landslides, travelling on different but nearby drainage channels. This does not actually happen in reality. In such case, it is suggested to reduce the size of the influence zone to avoid smoothing of particles across clusters.

3 COUPLING OF SPH AND GIS

With the emerging technology of GIS, the geotechnical professionals rely increasingly on the capability of GIS to display and analyse spatial data in relation to the design and study of natural terrain hazards and their mitigation measures. Throughout the years, ArcGIS are widely adopted in the geotechnical industry to analyse and exchange spatial data for planning, investigation and design purposes. In this respect, an ArcGIS application has been developed which empowers the geotechnical professionals to carry out their SPH analysis effectively and efficiently. The ArcGIS application comprises three modules, viz. input module, SPH module and post-processing module, which are illustrated in Figure 1. The modules are connected seamlessly such that there is no need to export data from one module to another manually.

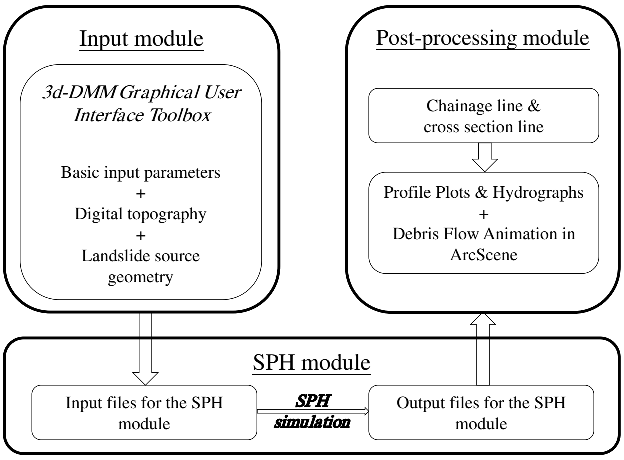

Figure 1. The three modules of the ArcGIS application

Figure 2a shows the graphical user interface of the ArcGIS application. The input module is responsible for guiding the user to set up the SPH model on the ArcGIS platform in a step-by-step manner. In particular, the module converts raw topography data (e.g. Light Detection and Ranging (LiDAR) point clouds) to the grid-based topography input data for SPH analysis. The module offers an option to trim the topography at the source location as a result of the detachment of debris material. After the user has entered all the input data, the SPH module is triggered which is capable of running on multiple processors. Based on the computed attributes of the SPH points (e.g. debris thickness, location, velocity), the SPH module prepares the data files for the post-processing module to display the results on the ArcGIS platform. Important design plots such as the velocity profile of landslide debris along its flow path, and the time history of the velocity and thickness of the landslide debris passing through a user-specified location in the flow path are available. Export of data to Microsoft Excel format for further analysis is also enabled. Furthermore, landslide animation in three dimensions can be generated in order to facilitate the review of the simulated flow process (see Figure 2b).

Figure 2. a). Graphical user interface of the input module and b). landslide animation in three dimensions

4 VALIDATION OF 3D-DMM

Six historical landslides were back-analysed in the validation exercise of 3d-DMM (Table 1). The Voellmy model (Voellmy, 1955) was adopted to model Cases No. 1, 3, and 4, which are channelised debris flows (GEO, 2011), as well as Case No. 5, which is a landslide within topographic depression (GEO, 2013). In contrast, the friction model was adopted to model Cases No. 2 and 6, which are open hillside failures (GEO, 2012b). The Voellmy model considers apparent angle of basal friction and turbulent coefficient in modelling basal resistance, whereas the friction model considers apparent angle of basal friction only. The apparent basal friction angle relates to the flow resistance due to the frictional interactions between the landslide debris and the channel bed, whereas the turbulent coefficient relates to the flow resistance due to turbulence and drag.

The apparent angle of basal friction of each case were determined by a preliminary back analysis of the six landslide cases using 2d-DMM (Kwan and Sun, 2006) and Particle in Cell (PIC) code (Kwan and Sun, 2007). For each of the six landslide cases, the apparent angle of basal friction that closely reproduced the flow velocity and runout distance of the landslide in the preliminary back analysis were adopted and fine-tuned, if necessary, in the back analysis of the 3d-DMM. The turbulent coefficient for Cases No. 1, 3 and 4 followed the recommendations given in GEO (2011), and Case No. 5 followed that of GEO (2013). The recommendations were made based on back analysis of historical landslides in Hong Kong. Table 1 shows the input parameters of the six validation cases.

Due to the page limit, only the results of one channelised debris flow, viz. the 2008 Yu Tung Road Landslide and one open hillside failure, viz. the 1995 Fei Tsui Road Landslide are elaborated in this paper. The results of other landslide cases are given in Law et al. (2016). Details of the 2008 Yu Tung Road Landslide and 1995 Fei Tsui Road Landslide are documented in GEO (2012a) and GEO (1996) respectively. Figure 3 shows the velocity profiles of debris front along chainage for the 2008 Yu Tung Road Landslide. Both the published velocity data from GEO (2012a) (shown in dots) and the computed data using 3d-DMM (shown in solid line) are presented in the figure. In the 3d-DMM analysis, the frontal velocity was calculated by the average tangential velocity of the foremost 10% of the smoothed particles that simulate the landslide debris. It was noted that the frontal velocities calculated using 3d-DMM match reasonably well with the field data.

Figure 4 shows the comparison between the simulated debris profiles and the field evidence (shown as the solid outline) of the 1995 Fei Tsui Road Landslide. The simulated debris deposit spreads across Fei Tsui Road by an extent that matches with the site measurement.

Table 1. Summary of cases in the validation exercise

No.	Case	Source volume (m^3)	ϕ (°)	ξ (m/s^2)	ϕ_i (°)	B
1	2008 Yu Tung Road Landslide	2,600	8	500	30	4
2	1995 Fei Tsui Road Landslide	14,000	22/35(1)	NA(2)	30	4
3	1999 Sham Tseng San Tsuen Landslide	600	8	500	30	4
4	1990 Tsing Shan Landslide	4,000	15	500	30	4
5	2003 Kau Lung Hang Shan Landslide	180	17	1,000	30	4
6	1995 Shum Wan Landslide	26,000	19	NA(2)	33	4

Notes:
(1) The apparent friction angle of 22° was adopted for landslide source area due to the presence of the kaolinite-rich layer. In contrast, a higher base friction angle of 35° was used for movement of the landslide debris over Fei Tsui Road.
(2) Friction model is adopted in the simulation, and therefore turbulent coefficient is not applicable.

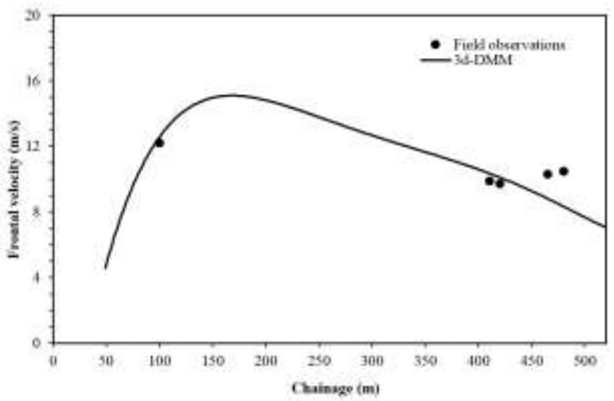

Figure 3. Comparison between the computed velocity profiles using 3d-DMM and field evidence of debris flow above Yu Tung Road in June 2008

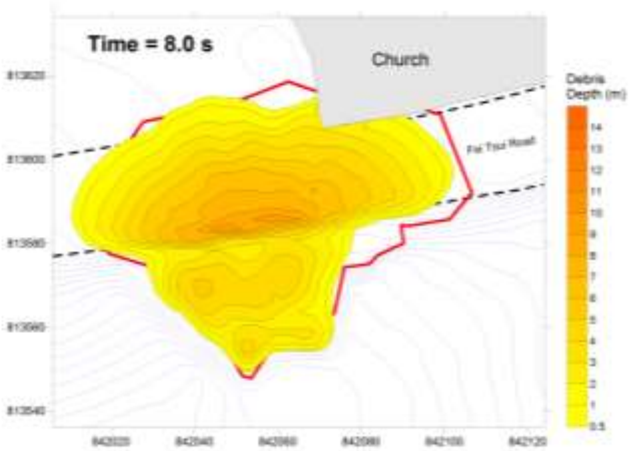

Figure 4. Comparison between the field observation (solid outline) and the simulated debris profiles using 3d-DMM

5 CONCLUSION

A new three-dimensional numerical code called 3d-DMM, based on SPH approach, Saint-Venant shallow water assumption, and Voellmy rheology, has recently be developed to facilitate quantitative assessment of debris flow mobility and design of risk mitigation measures in Hong Kong. In addition, an ArcGIS application has been developed which enables SPH analysis to be carried out on the ArcGIS platform, thus facilitating geotechnical professionals to carry out SPH analysis more efficiently. The 3d-DMM was validated by the back analysis against a total of six historical landslides in Hong Kong. Findings of one channelised debris flow case and one open hillside failure case were presented. It is observed that 3d-DMM produces results are consistent with the field observations of these landslide cases.

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