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A quasi-three-dimensional spring-deformable-block model for runout analysis of rapid landslide motion

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ABSTRACT

Assessment of landslide hazard often requires a good knowledge of the landslide characteristics. To investigate the dynamic runout process of the landslide across a 3D terrain, a quasi-three-dimensional model using spring-deformable-block model is proposed. On the assumption that the motion of landslides is continuous and variable, the sliding body is divided into lots of columns. The model is based on a stability analysis of landslides and allows the deformation of sliding body. Considering the force and moment equilibrium of deformable columns and the principle of conservation of energy, a quasi-three-dimensional sliding body is simplified by a series of deformable blocks with different dimensions. Then, the sliding body acceleration, velocity and displacement formulas are established accordingly. Correlating relatively well with the discrete element method, the present results are satisfactory in describing the dynamic process of landslides and predicting the impact areas of the post-failure sliding body. Finally, the present model is applied to analyze the sliding time, the maximum velocity and displacement of the sliding body of Jiweishan landslide in Wulong, Chongqing Southern China. When comparing with distinct element method, the model shows generally good agreement with them.

1. Introduction

Landslide which is defined as the movement of a mass of rock, debris or soil down a slope is characterized by long-runout displacements and high velocity (Cruden, 1991). Even far away from the origin of the slope failure, significant destruction can still be brought by rapid landslides through the sliding path. However, sometimes their potential for destruction cannot be practically reduced by reinforcement of the source area (Hungr, 1995). Prediction of post-failure motion is needed in the hazard assessment as an important part in case that a potential source of a landslide is detected. Therefore, engineering risk analysis emerged, especially the runout analysis which is applied to estimate the potential hazard area (Hungr, 1995). In order to design protective measures, runout parameters such as the maximum displacement reached, the landslide velocity, and the distribution of the deposits should be determined through quantitative method during the runout analysis.

At present, both empirical and analytical methods are adopted in predicting the motion of a landslide. By using the data observed, empirical methods are able to qualitatively estimate the extent of the impact zone. Among them, the angle-of-reach method is a kind of commonly used empirical method to estimate the runout displacement. The main idea is to use simplified plots and regression equations to establish a relationship between the angle-of-reach and other parameters describing the post-failure motion of landslides. Based on the relationship between the angle-of-reach and the volume of the sliding body, the methods have been applied in Hong Kong (Lau and Woods, 1997; Wong and Ho, 1997). Due to the change in terrain along the path, sometimes this method cannot obtain a reasonable result (Franks, 1999). Though the empirical methods offer a simple way for runout analysis, there is an obvious limitation that information on kinematic parameters is not available to obtain. Besides, the dependence on a large database of field observations is also restrictive (Chen and Lee, 2003).

Analytical methods consist of three broad categories, which are lumped mass method, continuum mechanics model (Pudasaini and Hutter, 2007), and distinct element method, respectively. Lumped mass method simplifies the motion of the sliding body as a single point with gravity. Then, particle kinematics and the principle of conversation of energy are adopted for investigating the post-failure motion. The lumped mass models (Perla et al., 1980; Hutchinson, 1986) shared the same restriction that the internal deformation has not been considered. Despite the fact that the reasonable approximations to the motion of the center of gravity were provided, Evans et al. (1994) pointed out that these models above are unable to simulate the motion of the flow front, which is an important part in the runout analysis.

Hungr (1995) indicated that the existing continuum mechanics models can be divided with the distinct rheological formulae in use. Based on the Bingham rheological model, many authors established their analysis in the conventional Eulerian framework in which fixed

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reference grid is used (e.g. Jeyapalan, 1980; McEwen and Malin, 1989; Sousa and Voight, 1991; O'Brien et al., 1993). For the purpose of simulating the highly unsteady character of landslide motion, Potter (1972) emphasized the advantage of the moving Lagrangian reference frame. A two-dimensional Lagrangian frictional model proposed by Savage and Hutter (1989) is capable to simulate the flow of dry sand. A quasi-two-dimensional continuum model (DAN) presented by Hungr (1995, 1998) has already been applied to the runout analyses of landslides in Hong Kong. The model simulated post-failure motion along a prescribed two-dimensional (2D) path. However, it is well known that a landslide is a spatial event consisting of the motion of forward pushing and lateral spreading in response to local topography. Due to the multi-dimensional property, it is difficult to use the DAN model to describe the spatial impact without resulting in large errors. In response to this issue, adapted models have been proposed by Gray et al. (1999), Chen and Lee (2000), Denlinger and Iverson (2001), Iverson and Denlinger (2001), Pudasaini and Hutter (2003), and Pudasaini et al. (2005). Nevertheless, some materials, such as soil, can exhibit continuous or discontinuous behavior, depending, e.g., on the density and stress. However, the present continuum models may not be able to deal with this problem.

For this purpose, the distinct element method in 2D (PFC2D) and 3D (PFC3D) was used by Tang et al. (2009), Lo et al. (2011), and Teufelsbauer et al. (2011), respectively, to simulate the post-failure motion of the landslide. Due to the limitation of the modeling techniques and the difficulties in parameter selection, this method can't be regarded as a general and verifiable design tool for runout analyze. Recently, there have been some new model developments, including the two-fluid model by Pitman and Le (2005), and the general two-phase debris flow model by Pudasaini (2012) that includes several important physics of the real two-phase mass flows as a mixture of solid particles and fluid with strong phase-interactions. In addition, many laboratory experiments have been conducted to investigate the post-failure motion. McDougall and Hungr (2004), Iverson (1997) and Denlinger and Iverson (2001) have successfully conducted controllable flume experiments by adopting constitutive relationships from grain–fluid mixture theory. Furthermore, the experiment conducted by Liu et al. (2013) simulated collapse of granular slopes and focused on the internal deformation of the sliding body.

Usually, landslides and avalanches are modeled by quasi-three-dimensional, or effectively two-dimensional models in which the deformations are geometrically quasi-three-dimensional, but velocity-wise depth-averaged, and thus, two-dimensional (Pudasaini and Hutter, 2007). By applying innovative pressure- and rate-depended Coulomb-viscoplastic deformation and sliding law, recently, Domnik and Pudasaini (2012) and Domnik et al. (2013) presented full-dimensional granular flow model which reveals both the solid-like and fluid-like regimes during the flow and deposition processes. From an application point of view, the key issues are how to determine the physical and mechanical parameters and how to apply it to engineering problem in a simple way. For, here, we intend to develop a simple model which can realize the visualization of the runout process.

In this paper, the sliding body will not be viewed as a rigid one. Here, the sliding body will be modeled as a 3D deformable material, which is characterized as the variance of the deformation, velocity, displacement at different parts of the sliding body. Multi-directional movement and internal forces between columns are discussed as well. Firstly, a quasi-three-dimensional spring-deformable-block model is established. Then, imbalance thrust force method is used to establish the initial equilibrium equation and the initial acceleration is obtained by surplus sliding force. After that, the initial inter-column forces caused by the acceleration are used to calculate the acceleration of each column at any time step. In the end, basic kinematics principle is adopted to calculate the velocity of every column. The improved 3D slice method is employed to simulate the motion of the sliding body from initiation to deposition. The runout parameters such as the maximum displacement, the maximum velocity and the sliding time are obtained. Subsequently, the present model is applied to analyze the dynamic runout process of Jiweishan landslide in Chongqing, southern China.

2. Principle of 3D deformable block model for landslide

The sketch of quasi-three-dimensional landslide motion is shown in Fig. 1. In terms of a local Cartesian coordinate system (x, y, z), x and y are aligned with the two motion directions, and z corresponds to the vertical direction. The sliding body, divided with vertical interfaces, consists of m rows in the x direction and n columns in the y direction. $z_1 = g(x, y)$ is the free surface of the landslide, and $s = f(x, y)$ is the slip surface.

Stress state on a column is schematically shown in Fig. 2. Each column is labeled by superscripts i and j, which represent the serial number of row and column, respectively. The weight of column is denoted by $W_{i,j}$. The normal force and shear force acting on the slip surface are denoted by $N_{i,j}$ and $S_{i,j}$, respectively. Performed normal to the lateral surface, $E_y^{i,j}$ represents the inter-row forces. $H_y^{i,j}$ and $T_y^{i,j}$ represent the horizontal and vertical shear forces acting on the lateral surface, respectively. The inclinations between the slip surface and the negative directions of x-axis and y-axis are denoted by $\alpha_x^{i,j}$ and $\alpha_y^{i,j}$. The widths of the columns in x, y and z directions are denoted by e, b, and h, respectively.

For simplicity, a number of classical assumptions applied by previous workers (Spencer, 1967; Fan et al., 1986; Lam and Fredlund, 1993) are used to derive the governing equations:

(a). It is assumed that the base of the column is a plane, and the acting points of the normal force $N_{i,j}$, the shear force $S_{i,j}$ are on the geometric center of the lateral plane. Besides, the weight $W_{i,j}$ acts on the centroid of the column, as shown in Fig. 2. All the slip surfaces of the columns satisfy the Mohr–Coulomb criterion.

(b). When the sliding body moves forward, for simplification the forces normal to yoz plane can be ignored. The values of horizontal shear forces $T_x^{i,j}$ and $T_y^{i,j}$ which are acting on four lateral surfaces are supposed to be zero. Similar with limit equilibrium method, the location of the acting point of $E_y^{i,j}$ is one third of the average heights of the lateral surface.

(c). The interaction force between the column (i, j) and the column $(i, j-1)$ is denoted by $G_{i,j}$, which is the resultant force of $E_x^{i,j}$ and $H_x^{i,j}$. Corresponding to the two-dimensional Spencer's method, we assume that the inclination of $G_{i,j}$ and the x-axis is a constant which is denoted by β.

(d). The inclination of the shear force $S_{i,j}$ and the x–z plane is ρ. We assume that ρ is positive when the z-axis component of $S_{i,j}$ is positive.

The direction cosine of normal forces $N_{i,j}$ and shear forces $S_{i,j}$ over the slip surface is denoted as (n_x, n_y, n_z) and (m_x, m_y, m_z), respectively. Due to the intersection angle between $N_{i,j}$ and the z-axis is less than 90°, the value of n_z should be positive. Therefore, the direction cosine of normal forces $N_{i,j}$ can be described as

$$n_x, n_y, n_z = \left(-\frac{1}{\Delta}f_x', -\frac{1}{\Delta}f_y', \frac{1}{\Delta}\right) \tag{1}$$

where $\Delta = \sqrt{1 + {f_x'}^2 + {f_y'}^2}$.

Based on the geometry relationship, we have

$$\tan\alpha_x = f_x', \quad \tan\alpha_y = f_y'. \tag{2}$$