3-D Dynamic Simulation and Visualization of Landslide Models
- A Case Study of the Shum Wan Road Landslide in Hong Kong

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Abstract: This paper builds a group of landside-related models including the model of geometric and physical parameters of landslide, sliding direction and stability coefficient model, specific stability coefficient model based on dynamic geographical environments, and dynamic process model of landslide. The dynamic relationship between landslide's stability coefficient and landslide band soil's water content, and internal cohesive force under varied space-time distribution are studied. A landslide simulation and visualization system is designed and developed for model computation and 3-D visualization of landslide process. The system and landslide-related models are used for studying the Shum Wan Road landslide in Hong Kong.

Key words: Landslide, application models, 3-D digital simulation, 3-D visualization

1. Introduction

On August 13,1995, a landslide took place at the hillside above Shum Wan Road, Aberdeen (Fig. 1), causing the collapse of a 30m long section of Nam Long Shan Road (GeoEO,1996). The landslide debris crossed Shum Wan Road and damaged three shipyards and a factory near the seafront. The landslide resulted in two fatalities, and five other people were injured. Fig.2 shows the site of the Shum Wan Road landslide.

Fig. 1 The landslide above Shum Wan Road on August 13,1995

Fig. 2 The geographic location of the Shum Wan Road in Hong Kong

In this paper, we aim to explore the mechanism and behavior of the Shum Wan Road landslide through the building and implementation of digital landslide models. A landslide simulation and visualization system is designed and developed to manage varied of data, to conduct model computation, and to implement visualization of landslide process. This research on the virtual reconstruction of the Shum Wan Road landslide may provide an advanced way for forecasting and preventing landslides.

2. Representation of landslide geometric shape and computation of landslide-related parameters

Digital terrain models (DEM) are used to represent landslide geometric shape, which includes shape definitions of slope surface and slide surface (Li, 1998). In view of the computation of forces regarding landslide and simulation of landslide behavior, it is the convenient way to use grid-based DEMs to simulate slope surface and slide surface.

Slope surface models are generated usually through TIN building and interpolation based on terrain contour or sampling points mapped before landslide. Generally, slide surfaces of landslide aren't mathematical surfaces for their complicated shapes, that is to say, they cannot be expressed exactly by simple mathematical expressions. DEMs are also employed to represent slide surfaces. In this research, we get the slide surface model through the interpolation of discrete points (including points of landslide boundaries) investigated after the Shum Wan Road landslide. Fig. 3 and Fig. 4 show the slope surface and the slide surface of the Shum Wan Road landslide respectively.

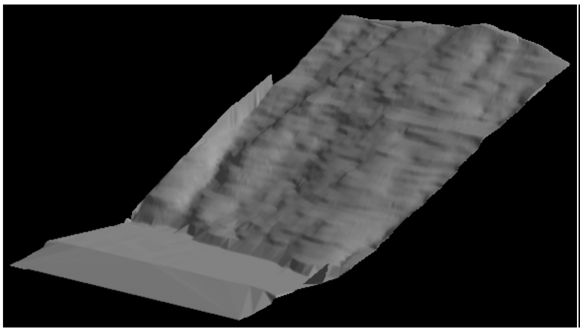

Fig. 3 The slope surface of the Shum Wan Road landslide

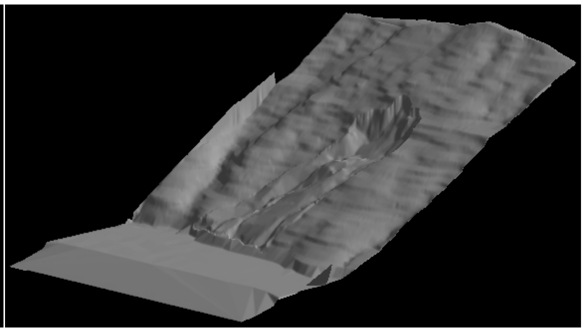

Fig. 4 The slide surface of the Shum Wan Road landslide

Based on the slope surface model and the slide surface model, the following physical and geometric parameters pertaining to landslide can be computed:

(1) thickness and volume of landslide body,
(2) length and width of landslide body,
(3) obliquity and direction of every grid above slide surface, and
(4) cross-sections.

3. Computation of sliding direction and stability coefficient of landslide

First, the concept of stability coefficient along landslide's direction is established. Then, the sliding direction and stability coefficient of landslide are obtained through the computation of the minimum stability coefficient.

The following is the method of calculating sliding direction and stability coefficient of landslide. Assume that A_0 represents direction, the computation of stability coefficient of landslide of A_0 is as follows(Li, 1999; Xu,1996):

$$K_{A_0} = F1/F2 = \sum_{i=1}^{m}\sum_{j=1}^{n}(W_{ij} \cdot \cos\alpha_{ij} \cdot \tan\varphi_{ij} + C_{ij} \cdot S_{ij} / \cos\alpha_{ij}) / \sum_{i=1}^{m}\sum_{j=1}^{n}(W_{ij} \cdot \sin\alpha_{ij}) \quad (1)$$

$$\cos\alpha_{ij} = \sec\Delta A_{ij}\sqrt{\tan^2\alpha_{ij} + \sec^2\Delta A_{ij}} \quad (2)$$

$$\sin\alpha_{ij} = \tan\alpha_{ij} / \sqrt{\tan^2\alpha_{ij} + \sec^2\Delta A_{ij}} \quad (3)$$

$$\Delta A_{ij} = A_{ij} - A_0 \quad (4)$$

where: F1 is the anti-sliding force, F2 is the sliding force, W_{ij} is the weight of a grid at the location (i, j), A_0 is the direction, A_{ij} is the aspect of a grid of the slide surface at the location (i, j), α_{ij} is the slope of a grid of the slide surface at the location (i, j),

φ_{ij} is the angle of internal friction of a grid at the location (i, j), C_{ij} is the coefficient of internal cohesive force of a grid at the location (i, j), S_{ij} is the area of a grid at the location (i, j) , m and n are the numbers of grids of the slide surface model in row and column respectively.

A variety of stability coefficients along different directions are worked out. There are numerous stability coefficients of different directions, with the minimum as the stability coefficient of the landslide and its corresponding direction as the sliding direction of the landslide. In order to improve accuracy and reduce calculation time, we carry out iterative and gradual computation to get the sliding direction and stability coefficient of the landslide, whose process is demonstrated as follows: first , we estimate an approximate sliding direction, and suppose two wide ranges at both sides of the direction respectively. Within the ranges, a number of stability coefficients are computed with a comparatively wide interval. Among the numerous stability coefficients, the minimum can be found, and the corresponding direction will replace the former sliding direction, and become the new sliding direction to repeat the above process. The above computation will be ended until the value of the new sliding direction minus the former sliding direction less than a predefined minimum value. Meantime, the last sliding direction and the corresponding stability coefficient of landslide can be obtained. In the case study of the Shum Wan Road landslide, we ran the computation under the condition of no precipitation, and Table 1 shows the computation process and last results. The last least stability coefficient is 1.2105 and the corresponding sliding direction is 257.75 degree.

Table 1 results of sliding direction and stability factor of the Shum Wan Road landslide

Times	Angle interval (degree)	Sliding direction(degree)	Angle range(degree)	Stability coefficient
1	2	243.000	185-265	1.4448
2	1	252.000	223-263	1.2830
3	0.5	256.500	242-262	1.2340
4	0.25	257.750	251.5-261.5	1.2105
5	0.125	257.750	250.25-260.25	1.2105

4. Initiation mechanism of landslide

Water takes a great part in landslide. Especially infiltration of precipitation influences the water content of landslide body greatly. It can increase the weight and volume of landslide body, decrease intensity of band soil, and decrease the stability of landslide body. By analyzing the water content and stability coefficient of the landslide body quantitatively, we develop a new approach to studying the initiation mechanism of landslide on the basis of rock physical parameters.

4.1 The initiation mechanism of landslide

The following demonstrates the initiation mechanism and the means to conduct dynamic computation of stability coefficient of landslide under continual precipitation.

For a convenient discussion, simplified computation of stability coefficient K_t at time t under continual precipitation is as follows (Li, 2001) :

$$K_t = \tan\overline{\varphi} / \tan\overline{\alpha} + \overline{C}_t /(\overline{h} \cdot \overline{P} \cdot \sin\overline{\alpha}) \tag{5}$$

$$\overline{C}_t = e^{a\overline{\omega}_t + b} \tag{6}$$

$$\Delta\omega = v \cdot t \cdot (H - h \cdot \ln(H / h + 1)) \tag{7}$$

$$\overline{P} = P_0 + \overline{\omega}_t \cdot n \tag{8}$$

$$\overline{\omega}_t = \omega_0 + \Delta\omega \tag{9}$$

where: $\overline{\omega}_t$, $\overline{\varphi}$, $\overline{C}_t$, $\overline{P}$, $\overline{\alpha}$, $\overline{h}$ represent the average water content of soil body, average angle of internal friction, average internal cohesive force, average unit weight, average slope and average thickness of the slide surface. v is the infiltration rate, n is the porosity, P_0 is the initial unit weight, ω_0 is the initial water content of soil body, $\Delta\omega$ is the change value of water content of soil body, and h is the water depth on the ground.

Along with continuous increase of water content, and as the water content of band soil arrives at some certain value, the stability coefficient of landslide will keep going down to 1. This means that the sliding force is equal to the anti-sliding force. In this situation, once the water content increases by $\Delta\omega$, the sliding force will be more than the anti-sliding force. With a shearing effect, the internal cohesive force tends to be aero, which results in a bigger initial acceleration and makes landslide happen.

4.2 Digital simulation of initiation mechanism of landslide

In the above discussion, we've made a simplified computation of the stability coefficient by using average values of a number of parameters. However, the physical and geometric parameters of rock at different locations on the landslide surface are usually varied. Considering the different spatial distribution of landslide related parameters, the formula to calculate stability coefficient is as follows (Li, 2001):

$$K_t = \sum_{i=1}^{m}\sum_{j=1}^{n}(W_{tij} \cdot \cos\alpha_{ij} \cdot \tan\varphi_{ij} + C_{tij} \cdot S_{ij} / \cos\alpha_{ij}) / \sum_{i=1}^{m}\sum_{j=1}^{n}(W_{tij} \cdot \sin\alpha_{ij}) \tag{10}$$

$$W_{tij} = S_{ij} \sum_{l=1}^{H_{ij}} P_{tl} \cdot H_l \quad (11)$$

$$P_{tl} = P_{oij} + \Delta P_{tij} = P_{oij} + \omega_{tij} \cdot n \quad (12)$$

$$C_{tij} = e^{a\omega_{tij} + b} \quad (13)$$

$$\omega_{tij} = \omega_{0ij} + \Delta\omega_{tij} \quad (14)$$

$$\Delta\omega_{tij} = v \cdot t \cdot (H'_l - h \cdot \ln(H'_l / h + 1)) \quad (15)$$

where: W_{tij} is the weight of a grid at the location (i, j) at time t, α_{ij} is the slope of a grid of the slide surface at the location (i, j), φ_{ij} is the angle of internal friction of a grid at the location (i, j), S_{ij} is the area of the grid at the location of (i,j), H_{ij} is the thickness of the grid at the location of (i,j), H_l is the unit thickness, h is the depth of water on the ground, P_{tl} is the unit weight at the level of l at time t, P_{0ij} is the initial unit weight at the location (i, j), ΔP_{tij} is the change value of unit weight at the location (i, j) at time t, ω_{tij} is the water content of soil body at the location (i, j) at time t, n is the porosity, C_{tij} is the coefficient of internal cohesive force at the location (i, j) at time t, a and b are empirical coefficients, ω_{0ij} is the initial water content of soil body at the location (i, j), $\Delta\omega_{tij}$ is the change value of water content of soil body at the location (i, j) at time t, v is the infiltration rate, H'_l is the water depth in the soil body at the level of l, and h is the water depth on the ground.

In the case study of the Shum Wan Road landslide, we ran the computation under the condition of continual precipitation, and Table 2 shows the computation process and results including sliding direction, stability coefficient, anti-sliding force, and sliding force. In Table 2, the stability coefficient gradually decreases by from more than 1 to less than 1 with the continual precipitation. When the stability coefficient is 0.9183 (less than 1), the soil body starts to move and landslide happens.

Table 2 Digital Simulation of Landslide Initiation

Times	Sliding direction (Degree)	Stability Coefficient	Anti-Sliding force(t.)	Sliding force (t.)
1	243.000	1.2195	30620.82	25108.84
2	252.000	1.0797	29594.63	27411.08
3	256.500	1.0369	29441.88	28394.57
4	257.750	1.0169	29143.96	28659.39
5	258.875	1.0139	29293.13	28891.71
6	257.750	1.0104	28957.66	28659.39
7	252.000	0.9183	23218.26	25284.15

5. Process of landslide and digital simulation

Once landslide starts, the sliding body moves along the slide surface towards the direction of the thrust with a starting acceleration. The terrain surface along its movement will be the new slide surface until it stops completely on the terrain surface. It implies that the slide body moves along a changing slide surface. The direction for the next movement depends upon current directions of thrust and the acceleration. It will move along the direction of the least stability coefficient with biggest thrust and least resistance. The condition for the stopping of landslide is that the stability coefficient of sliding body is more than one and the velocity of movement is zero.

The procedure of digital simulation of the dynamic process is illustrated in the flowchart of Fig. 5.

In the case study of the Shum Wan Road landslide, we carried out the simulation of the dynamic process of landslide. Table 3 shows the some intermediate results of distance, stability coefficient, thrust direction, acceleration, and velocity.

Table 3 Digital Simulation of Landslide Dynamic Process

Distance(m)	Stability coefficient	Thrust direction (degree)	Acceleration (m/s^{-2})	Velocity (m/s^{-2})
0	0.9183	252.000	0.253	0
2	0.733	256.00	0.998	1.9
6.5	0.886	263.00	0.387	2.9
11.1	1.01	263.00	-0.12	3.14
16.1	1.112	263.00	-0.380	2.5
30.6	0.446	260.0	2.29	6.2

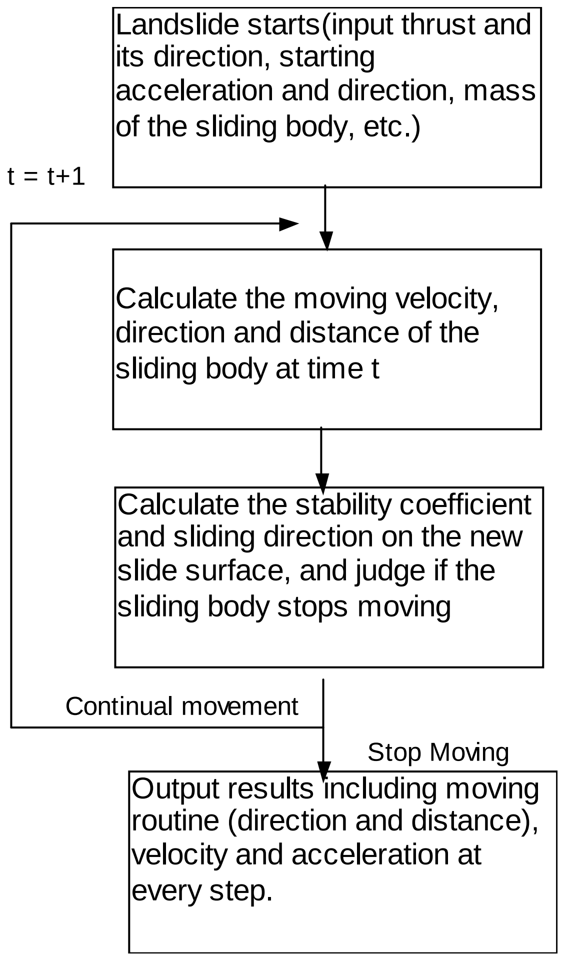

Fig. 5 The procedure of digital simulation of landslide process

6. A landslide simulation and visualization system

At present, it is difficult for us to apply common GISs to visually handling 3-D simulation of landslide (Bernard et al., 1998; Mason et al., 1994). In this paper, we designed and developed a landslide simulation and visualization system for managing landslide-related data and models, for implementing model computation, as well as for visualizing the slope surface, the slide surface, and landslide process. The system has four major components: spatial data base, model managing module, visualization module, and user's interface. Visual C++ and OpenGL are used for system development. Fig. 6 demonstrates the 3-D visualization of landslide process at different time.

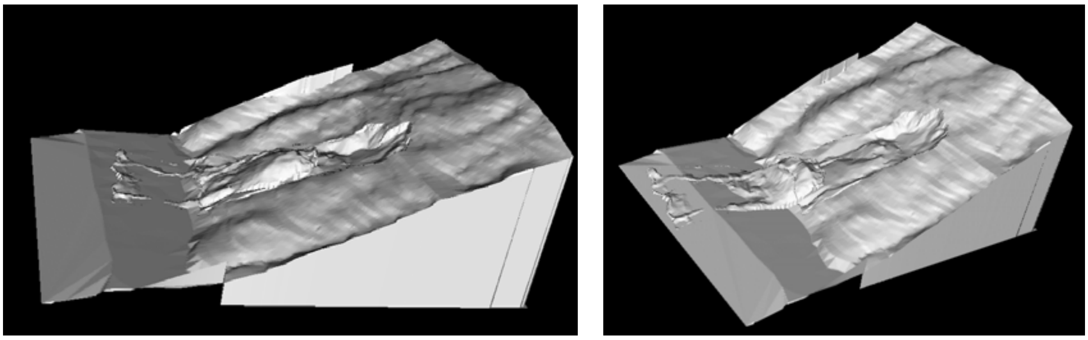

Fig. 6 3-D visualization of landslide process

7. Conclusions

This paper studies the influence of environmental factors of slide body (such as precipitation, underground water, and porosity) on the change of unit weight, cohesive force, angle of internal friction, and so on. A group of application models have been established to deal with landslide according to the landslide mechanism. These models can all be managed and computed in a landslide simulation and visualization system, which developed by our research group. Through a case study of the Shum Wan Road landslide in Hong Kong, the digital simulation of the landslide can help us deeply understand the causes and process of the landslide, and is of great value in forecasting and preventing of other landslides.

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