Application of three-dimensional discrete element face-to-face contact model with fissure water pressure to stability analysis of landslide in Panluo iron mine

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Abstract Three-dimensional discrete element face-to-face contact model with fissure water pressure is established in this paper and the model is used to simulate three-stage process of landslide under fissure water pressure in the opencast mine, according to the actual state of landslide in Panluo iron mine where landslide happened in 1990 and was fathered in 1999. The calculation results show that fissure water pressure on the sliding surface is the main reason causing landslide and the local soft interlayer weakens the stability of slope. If the discrete element method adopts the same assumption as the limit equilibrium method, the results of two methods are in good agreement; while if the assumption is not adopted in the discrete element method, the critical ϕ numerically calculated is less than the one calculated by use of the limit equilibrium method for the same C. Thus, from an engineering point of view, the result from the discrete element model simulation is safer and has more widely application since the discrete element model takes into account the effect of rock mass structures.

Keywords: face-to-face contact model, fissure water pressure, three-dimensional discrete element method, landslide.

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1 Introduction

Rock slopes usually contain many jointed surfaces such as joint fissure. When subject to water seepage, the jointed surfaces will induce many geologic disasters such as landslide and mudflow, and these will do great loss to the national economic development. Therefore, it is very important to deeply understand the mechanism of these disasters. Site observations and analysis on the landslide show that water is one of the key factors to induce landslide[1−8]. All methods calculating the stability of landslide consider the effect of groundwater pressure, for example, the limit equilibrium method considers it by increasing water pressure on sliding surface[9−11]. Discrete element method has different viewpoints. Since discrete element method was first proposed by Cundall, it has been widely used in geotechnical engineering[12−15]. Wang[12] coupled the fissure network seepage model and the discrete element method to analyze the stability of water filled rock slope and used it in engineering project. Jiao[13] simulated the moving regularity of groundwater in fissure using the discrete element method. All of these methods are Cundall model, which not only can reflect such large displacements as slipping, separation, toppling of contact surface among elements, but also can calculate the deformation and stress distribution of elements. In 1984, based on Cundall model, Dowding[16] developed NURBM face-to-face contact model. NURBM model places LP on the working faces instead of corners, and thus having obvious features in calculating the stability of rock mass. When calculating water pressure, NURBM model can directly convert water pressure acting on the working face to the force on LP. With the help of the three-dimensional discrete element face-to-face contact model with fissure pressure and by virtue of the actual state of landslide in Panluo iron mine where landslide happened in 1990 and was fathered in 1999, this paper simulates three-stage process of landslide under fissure water pressure in the opencast mine, analyzes occurring and developing reasons of landslide, and investigate the application of the discrete element method in actual projects.

2 Landslide in Panluo iron mine and reason analysis

2.1 Landslide general situation

Panluo iron mine, which lies in the west of Fujian Province, is a medium opencast mine [17] and produces 300000 ton of iron every year. The landslide process of this mine was divided into three stages, which happened in 1990 and was fathered in 1999. Because of a 5.3-grade earthquake in Taiwan Strait and several storms in 1990, the slope of the opencast mine damaged extensively and formed a U-shaped landslide (1# landslide). The potential avalanche amount is about 1000000 m^3. As shown in Fig. 1(a), the back boundary is distinct, two-flank boundary expands downward continuously and the tectonic movement of trailing fractures increases.

According to the survey results of engineering geology, 1# landslide was fathered primarily and at the same time, the monitoring system of landslide was installed. The monitoring results showed that fathering of landslide had obvious effects and the movement of 1# landslide had slowed down. But with the descending of stope, 2# landslide occurred in front of 1# landslide in 1991, as shown in Fig. 1(b). The level of the upper limb of 2# landslide is 940 m and the level of outlet is 910 m. The gliding mass is small, but slip velocity and slippage are great, trailing strews several meters, and frontal ground drum is 7.7 m. Because of unloading on its top, the landslide stabilized quickly. 1# landslide began to change, because 2# landslide occurred and storm and stope continued to fall. Furthermore, there was much heavy storm in 1997, 1# landslide extended backward

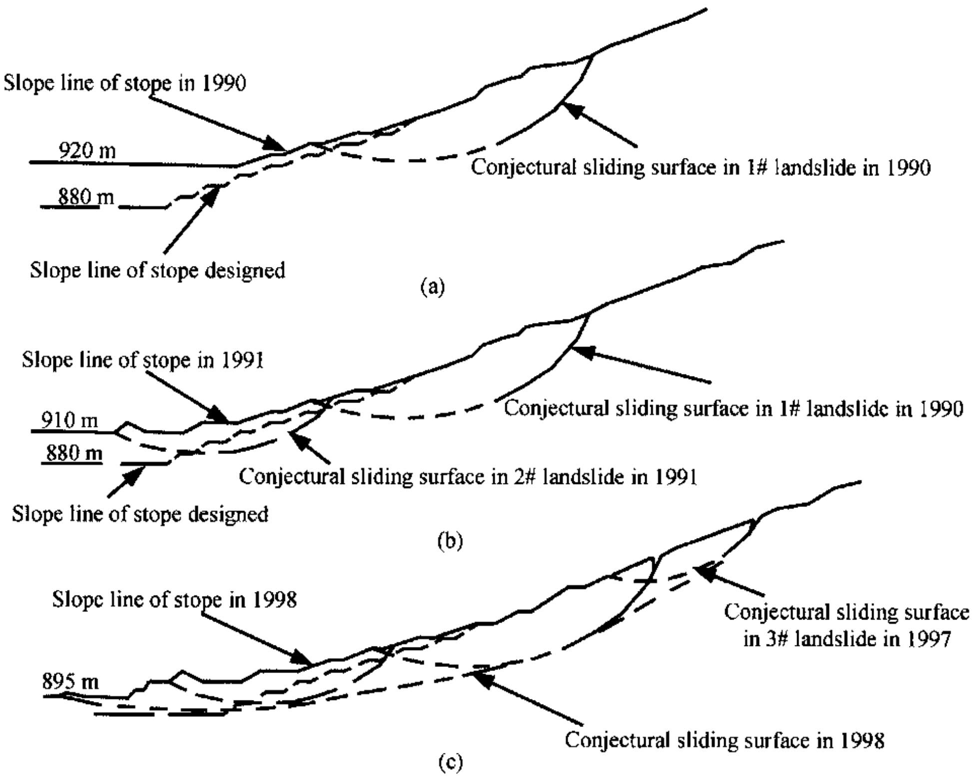

Fig. 1. Illustration of three-stage process of landslide.

and 3# occurred, as shown in Fig. 1(c). 1# landslide moved so excessively that free surface occurred in the back and there was water pressure on the sliding surface because of heavy storm. All of them caused 3# landslide that added gliding force to 1# landslide and aggravated the development of 1# landslide. Because of all the factors above mentioned, 1# landslide, 2# landslide and 3# landslide combined to a big landslide, as in Fig. 1(c). The whole landslide is shown in Fig. 2.

2.2 Genetic analysis of landslide

Monitoring results showed the slippage of landslide is closely related to rainfall. Light rain leads to small sliding, heavy rain leads to large sliding, and no rain leads to no sliding. Because sliding is great in rainy season and sliding does not happen in dry season, rainfall is one of the main reasons leading to landslide. Water affects the stability of landslide in the following two aspects: firstly, water can reduce the shear strength of weak interlayer on the sliding surface; secondly, water will seep through the fractures in the back of 1# landslide, produce artesian pressure in the sliding force of 1# and 2# landslide, and reduce the effective stress on the sliding surface.

3 Application of 3D face-to-face contact discrete element model to engineering

3.1 Calculation model and material parameter

Survey materials reveals that landslide is made of remaining soil and iron stone,

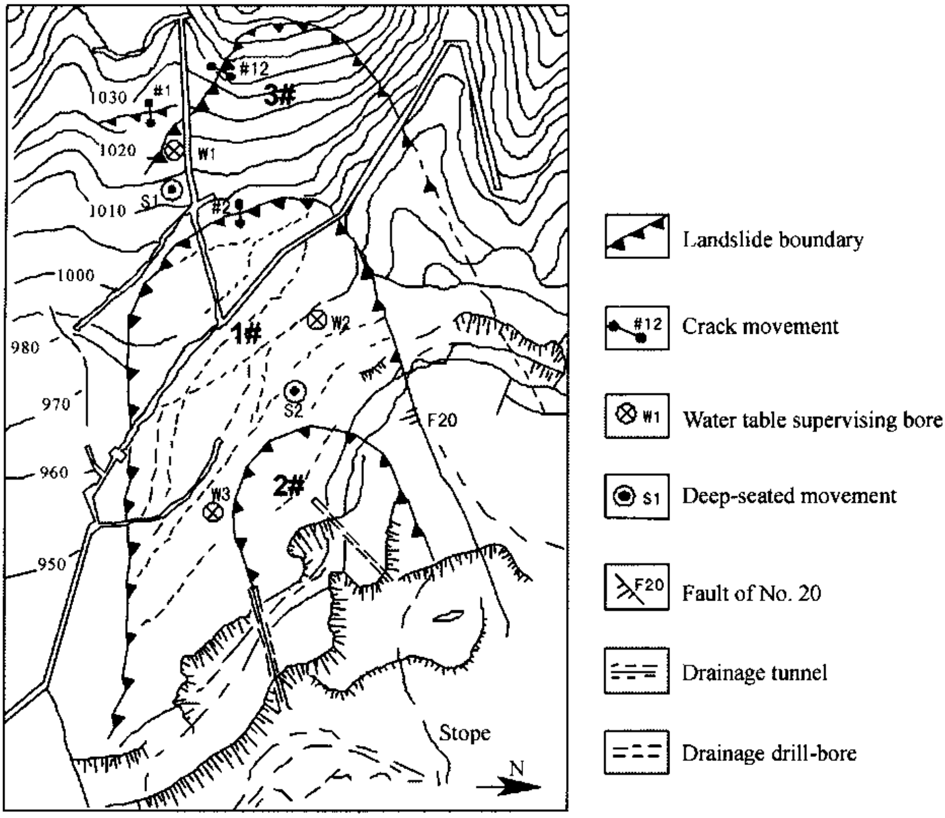

Fig. 2. The domain of landslide and monitored point, fathered engineering plane map.

Table 1 physical and mechanical index values of slope

Rock property	State	Volume weight (kN/m^3)	Water content (%)	Shear strength			
				Peak value		Residual value	
				c(kPa)	ϕ(°)	c(kPa)	ϕ(°)
Remaining soil	natural	17.0	41.0	13.0	25.0		
	saturated	17.5	49.0	11.0	18.5		
Slope soil	natural	18.5	30.0	39.0	22.0	18.0	16.5
	saturated	19.2	35.0	27.0	18.0		
Iron stone	natural	35		110	23.25		

and its physical and mechanical properties are listed in Table 1.

The whole landslide is composed of three sectors: 1# landslide and 3# landslide are the steepest (32 degree), 2# landslide's gradient is 16 degree, and anti-gliding sector of slope toe is about 4 degree. The landslide is thin (10 m) in the top and thick (30 m) in the bottom, as in shown Fig. 3. 1#, 2# and 3# index points are the locations of 1#, 2# and 3# landslide that are made of soil, and Fe index point is the represent of iron stone. As regulating measures such as top drainage and underground drying were executed, soil material parameter changed. Therefore, for the different simulating stages, both the calculation parameters and study regions vary dynamically. The calculation parameters are shown in Table 2.

Table 2 Calculation parameters

Rock property	Density (kg/m^3)	Poisson ratio	Elastic ratio (N/m^2)	Cohesion force (kpa)	Internal friction angle/°	Normal stiffness (N/m^2)	Tangential stiffness (N/m^2)
Slope soil	1800	0.4	1.0×10^9	27.0	18.0	3.0×10^9	2.0×10^9
Iron stone	3570	0.2	1.0×10^{10}	110.0	23.25	3.0×10^9	2.0×10^9
Gliding band soil before measuring	1800	0.4	1.0×10^9	9.0	15.0	3.0×10^9	2.0×10^9
Gliding band soil after measuring	1800	0.4	1.0×10^9	14.2	16.8	3.0×10^9	2.0×10^9

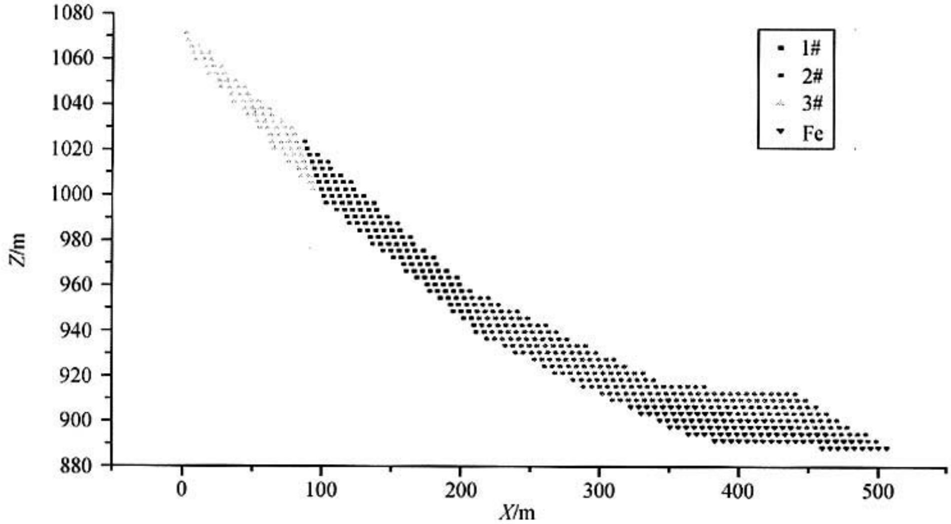

Fig. 3. Zoning map of rock and soil medium in landslide.

When the study domain is simulated by three-dimensional discrete block element, there are total 1650 elements. Structural geometric parameters, trend and dip of element division are shown in Table 3.x axis is sliding direction of landslide,z axis is height and y axis is width. This paper takes 18 m in width direction, so it can be thought that three-dimensional program is used to simulate two-dimensional question. The bottom of bedrock is fixed and the contact surface between the first layer of elements and bedrock is sliding surface. Gravity and fissure water pressure are considered in calculation.

Table 3 Joint parameters

Joint set	Joint spacing (m)	Joint inclination (degree)	Joint dip (degree)
1	6	90	0
2	4	90	90
3	6	0	90

3.2 Numerical simulation on the occurring and developing process of landslide

The calculation process is as follows: firstly, assume C=27 kPa and ϕ=18° and calculate landslide strength until the total energy is zero according to the known slope soil strength; secondly, obtain the initial stress and strain fields. Iron stone strength parameter does not change in the calculation because water affects it little, on the basis of which, take partial soil strength of sliding surface (C, ϕ) as the true sliding surface strength, calculate until it is stable and obtain true stress and strain.

(i) Numerical simulation on 1# landslide and analysis. Because of a 5.3-grade earthquake in Taiwan Strait and several storms in 1990, the slope of the opencast mine were damaged extensively and formed a U-shaped landslide (1# landslide). Only the effect of rain is considered in calculation, so it is rain that induces the decrease of partial C, ϕ values (in Table 2) of 1# landslide. According to the actual location of sliding surface and shear outset shown in Fig. 4, the calculated displacement vectogram is in agreement with the actual form, shown in Fig. 4.

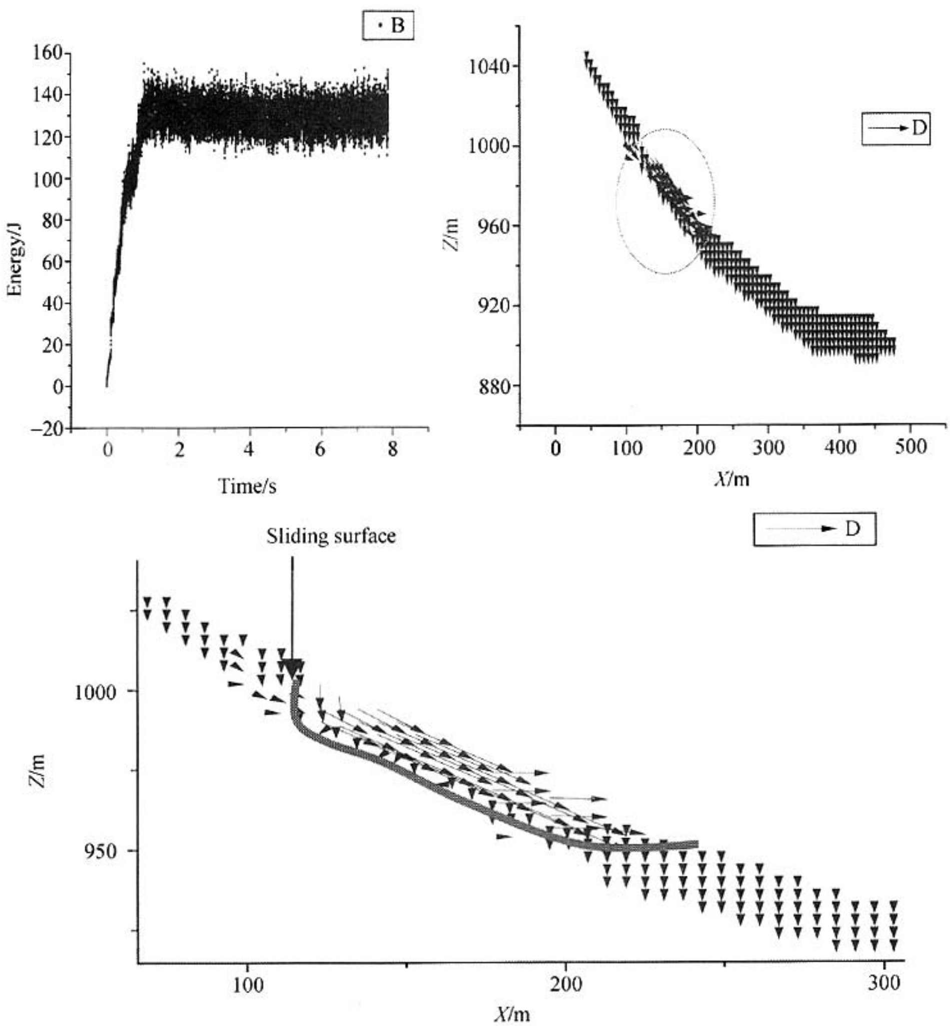

Fig. 4. 1# landslide energy, spatial location and local displacement vectogram.

(ii) Numerical simulation on combined landslide and analysis. 1# landslide was fathered and at the same time, monitoring systems was installed. Monitoring results show that 1# landslide moved slowly. But as stope fell, anti-sliding segment of slope diminishes and tensile fracture generates in the back of 1# landslide. Water infiltrated into sliding surface and caused artesian pressure, which is equal to γH (γ is water volume weight and H is pressure head). 2# landslide occurred with the help of rainwater, as shown in Fig. 1(b). Furthermore, there was much heavy storm in 1997, 1# landslide extended backward and induced 3# landslide, as in Fig. 1(c). 3# landslide applied gliding force to 1# landslide, which aggravated the development of 1# landslide. Because of all the factors above mentioned, 1# landslide, 2# landslide and 3# landslide combined a big landslide, as in Fig. 1(c).

Mechanical properties of rock blocks and joints are shown in Table 2. H is the elevation difference of tensile fracture of 1# landslide's trailing and sliding surface. The 1#, 2#, 3# landslide spatial location and local displacement vectogram are shown in Fig. 5. It can be concluded that if there is soft interlayer in local sector of slope, it will generate local sliding and tensile fracture in landslide's trailing, although landslide will not occur. Rainwater infiltrates into sliding surface in which shear strength is reduced and generates great artesian pressure in the sliding surface, then results in 2# landslide. The big

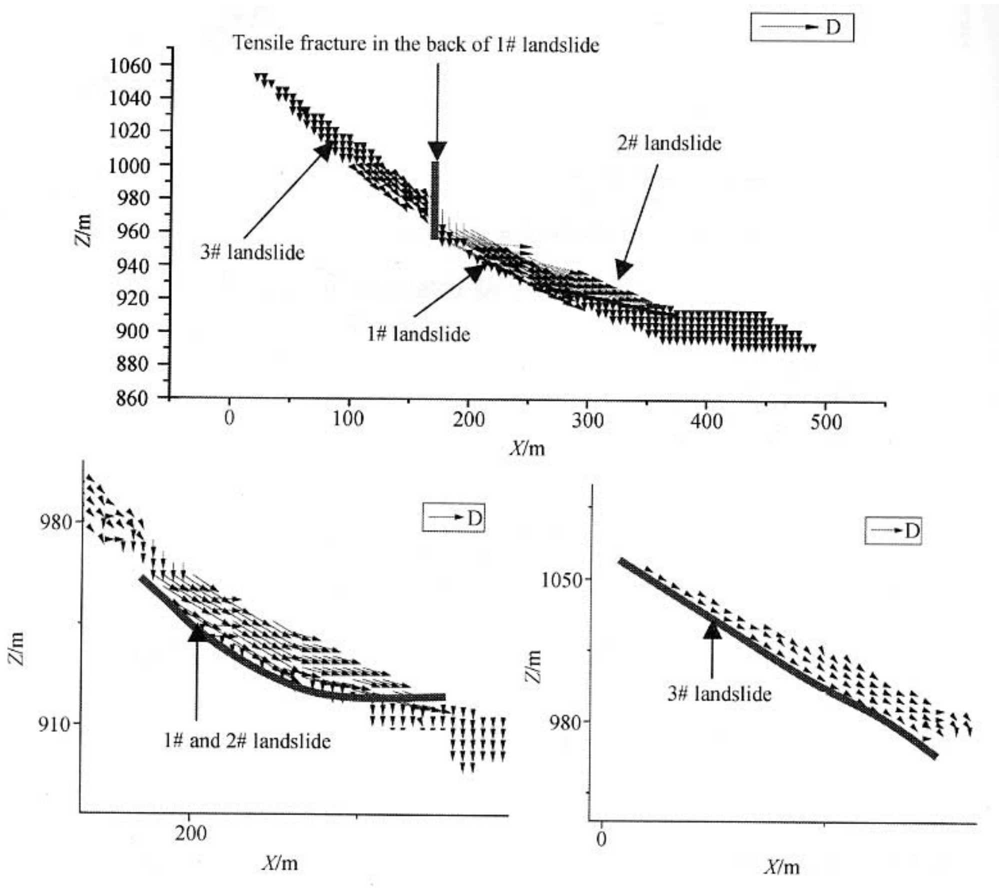

Fig. 5. 1#, 2#, 3# landslide spatial location and local displacement vectogram.

free surface in the back of 1# landslide forms 3# landslide, which affects the resistance to overturning of landslide.

(iii) Numerical simulation on landslide and analysis after fathering. Cut grade and reduce load for 1# and 3# landslide which is steep so as to diminish gliding force and add those soil to slope toe to increase anti-gliding force, at the same time, take measures to the water in slope. The above-mentioned measures get obvious effect. C and ϕ values after fathering are shown in Table 2. Calculate according to the surveyed conjectural sliding surface after fathering, and then get the energy map shown in Fig. 6(a) and the displacement vectorgram shown in Fig. 7. From the figure, it can be seen that slope becomes unstable and cannot in agreement with the actual engineering if we adopt the result that C=14.2 kPa and ϕ=16.8° which are surveyed. The reason includes: first of all, the mechanical index value obtained throng drill hole sampling is smaller, which is possibly connected with the disturbance of soil samples; secondly, sliding surface is not connected completely. Hence, keep C value invariable and calculate the critical friction angle ϕ_{cr}, get the energy map when ϕ is 19° and the slope is stable entirely, as

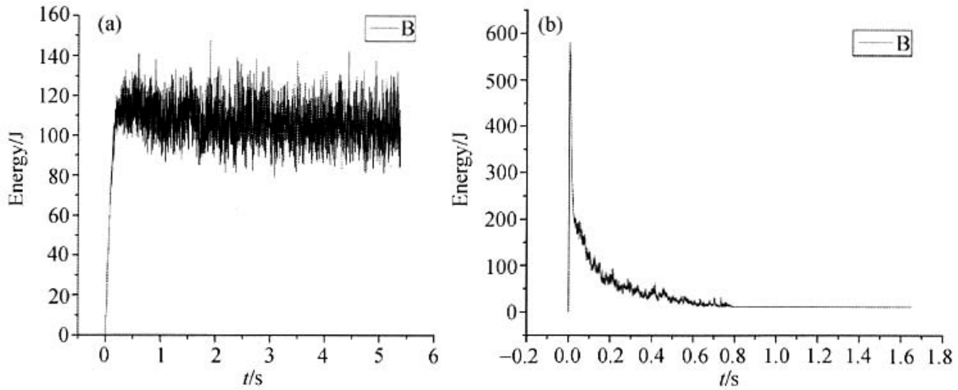

Fig. 6. (a) ϕ=16.8° energy map; (b) ϕ= 19° energy map.

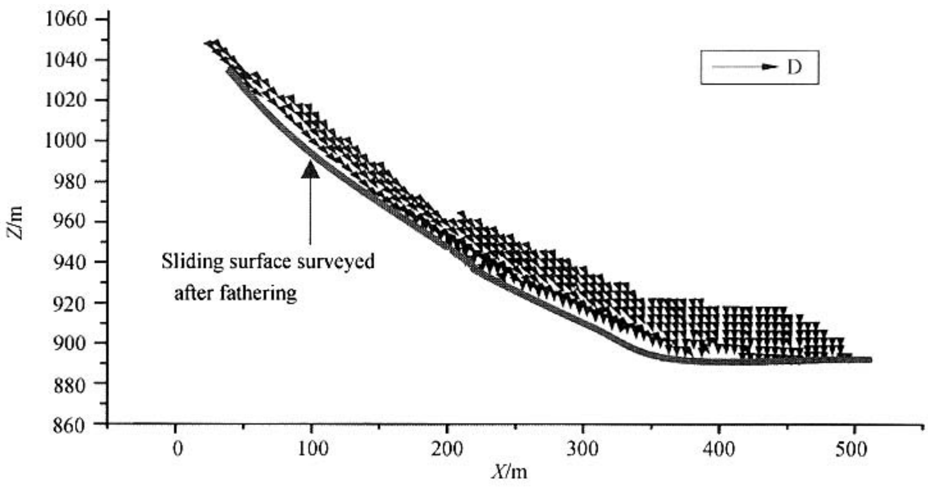

Fig. 7. ϕ= 16.8° displacement vectogram of landslide after fathering.

shown in Fig. 6(b).

(iv) Comparison of the discrete element model with the limit equilibrium model. To apply the three-dimensional discrete element face-to-face contact model to engineering problems, the assumption of vertical section method, which is made in the limit equilibrium method, is also adopted in the simulation, and the results calculated with the discrete element model is compared with the results calculated by the limit equilibrium method. Take C=14.2 kPa, the calculation results show that: if ϕ is equal to 14.0°, slope becomes instable. The energy map is shown in Fig. 8(a) and the displacement vectogram is shown in Fig. 9; if ϕ is equal to 15.0° degree, slope is stable and the displacement vectogram is shown in Fig. 8(b). So we can find if three-dimensional discrete element face-to-face contact model adopts the assumption used in the limit equilibrium method, the calculation results (C = 14.2 kPa, ϕ = 15.0°) of two methods are the same; but if the discrete element model does not adopt the assumption, the results are different that ϕ has difference of 4° when C is equal to 14.2 kPa.

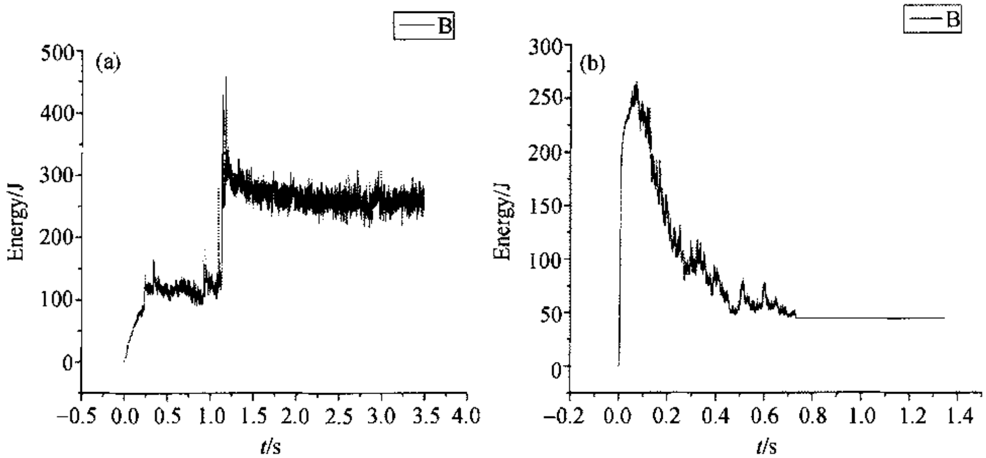

Fig. 8. (a) ϕ = 14° energy map; (b) ϕ = 15° energy map.

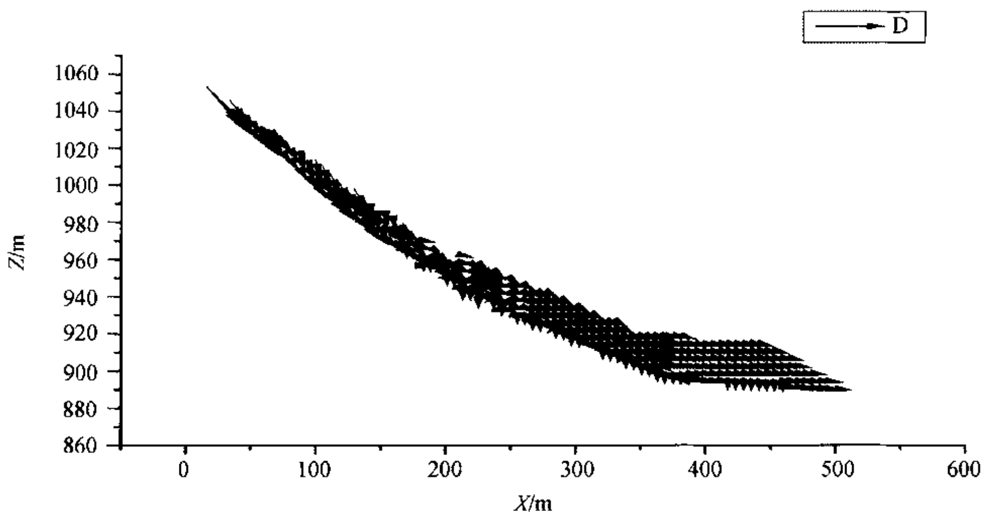

Fig. 9. C=14.2 kPa, ϕ = 14° displacement vectogram of landslide.

The difference reason is that the assumption made in the limit equilibrium does not consider the rotating and toppling of blocks, while the discrete element method can model slipping, rotating and toppling in the course of slide destabilization, thus more physically reflecting the true state of landslide. In this paper, the maximum slope angle of landslide is 32 degree and failure modes include sliding, toppling, or their combination. So the results of the limit equilibrium method are more dangerous, while discrete element method meets the truth better.

4 Conclusions

Using the three-dimensional discrete element face-to-face contact model with fissure water pressure, this paper simulates and analyzes the occurrence and development of landslide of opencast mine in Panluo iron mine. The simulation results are in agreement with actual engineering and the following conclusions are drawn.

First, simulation shows that there are soft interlays inside local slope which does not induce the whole destabilization of slope, but can induce local sliding and generate tensile fracture in the back of gliding mass. If rainwater infiltrates into sliding surface through fractures, it not only softens soil of sliding area but also results in great artesian pressure on sliding surface, thus weakening the stability of slope.

Second, the parameter values calculated with the discrete element model are higher than the experimental results obtained with geology drill hole sampling. The reason is that soil samples are disturbed in the course of sampling and cannot reflect true state, or sliding surface of landslide is not connected completely.

Third, if three-dimensional discrete element face-to-face contact model makes the assumption used in the limit equilibrium method, the calculation results of the two methods are in good agreement, which proves the reliability of the discrete element model. If the discrete element model does not make such assumption, the results have great difference and ϕ calculated by the limit equilibrium method is smaller when C is the same. From an engineering view of point, the discrete element model is safer and has much wider application since the discrete element model takes into account the effect of rock mass structures.

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