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China University of Mining & Technology, Beijing

Master Dissertation

Newton Force Monitoring and Numerical Simulation Analysis of "Landslide 2016-1101" in NanFen Open-pit Iron Mine

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Signature:_____________ Date:___________

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Abstract

NanFen open-pit iron mine is one of the largest black metallurgical mines in China with one hundred years of mining history. In recent years, as the mining up of the shallow resources and increasing of mining depth, the local slope reached 552 m (elevation 142-694 m). Because of the "V" shape of main stope section, the space on the bottom of stope became narrow and under the risks of rock rolling, landslides and other disasters. These are serious threats to personnel and mechanical safety. For the problems above, NanFen mine started the new phase of slope expansion and mining. In the last 3 years, landslide disasters have occurred many times during the slope expansion due to the old landslide bodies. In this paper, the characteristics of the whole destruction process of slope rock mass from cracks, expansion, penetration, disintegration and slippage are firstly revealed according to the evolution law of the monitoring and early warning curve of large deformation cable with constant resistance (NPR cable) in “landslide 16-1101”. Then, the mechanical model for large deformation numerical analysis of NPR cable is established using FLAC3D and 3DEC, and the whole process that the deposits load of “landslide 13-0223” induced “landslide 16-1101” is numerically simulated. Finally, comparing the measured results and simulated results of destruction characteristics of NPR cable and slope, it is found that there is a significant consistency between them. It is proved that the large deformation numerical analysis model of NPR cable can meet the large deformation of rock mass without being pulled off and broken, thus providing a theoretical basis of large deformation numerical simulation for other similar landslides.

Key Words: landslide disaster, large deformation cable with constant resistance (NPR cable), sliding force monitoring, numerical simulation, early-warning criteria

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Chapter 1 Introduction

1.1 Research background and significance

Landslide is a kind of geological phenomenon in which collapsing and sliding of slopes are triggered by gravity or other external factors, as well as shear displacement along a certain structural surface. Large deformation of landslides can be caused by deep mining of opencast coal mines, coal mining and combined mining in open wells in China, showing characteristics of wide distribution, high frequency and strong strength. Landslide disasters have led to huge threats to mining safety and sustainable mining in numerous mines, such as Antaibao opencast coal mine in Shanxi, open-pit coal mine in Fushun West and Pingzhuang West, and Nanfen open-pit iron mine in Liaoning, which is discussed in this paper.

Nanfen open-pit iron mine of Benxi Iron and Steel Group is the largest single open-pit mine in Asia[46], located in the northern part of Taizi River in Liaodong platform. And the ore mine accumulated in the iron rock section of Archean Anshan group with a monoclinic structure. The upper part of slopes is an anti-dip rocky slab, mainly with Mr12 and TMQ, of which the hardness (f) is 13-16 and the slope angle is 46.02°-48.60°[13] The lower part of slopes is a bedding rock slab, mainly with TMQ and Aml[43], of which the hardness (f) is 8-12 and the slope angle 35.18°-35.40°. The topography and geologic section of the stope are shown in Figure 1.1 and Figure 1.2, respectively.

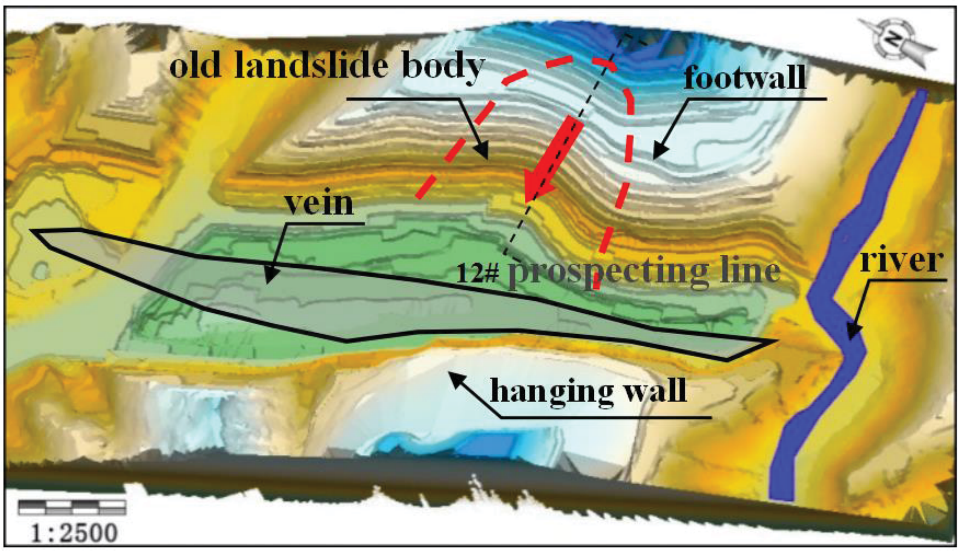


Fig.1.1 Topographic map of mining area

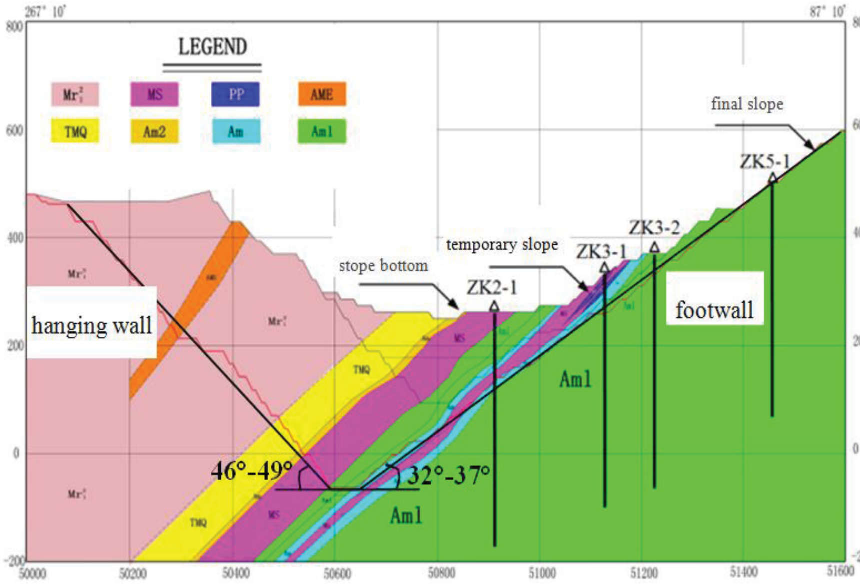


Fig.1.2 Geological profile (at 23 # prospecting line)

Since 1999, there are several large-scale landslides with a length of 252m, a width of 250m and a sliding direction of 270 ° due to the combined influence of special terrain and long-term mining. The landslide volume is about 52 million m^3, causing nearly 10 million tons iron unmineable in ten years which is a significant economic loss. In November 2000, Nanfen open-pit iron mine invested nearly 120 million RMB to develop an emergency treatment project in the potential area of landslide, including: drainage and cleaning works at the 370m platform and reinforcement of cable in the middle of 430-526m platform. In 2008, large deformation damage produced in the reinforcement project at the 430m platform due to the serious deformation of the slope, as shown in Figure 1.3.

Fig. 1.3 Large Deformation Damage Characteristics of Reinforcement Area on Platform 526m

In November 2009, a surface displacement automatic monitoring system was established to monitor the slope displacement in Nanfen open-pit iron mine. A total of

12 surface displacement monitoring points were distributed around the system, while only six monitoring points were left because of rolling stones impact in the operation process. On May 20th, 2010, a new small-scale landslide appeared on the north side of the 526m platform, and the monitoring points 21, 22, 23 were rearranged. Because cracks and displacements are not necessary and sufficient conditions for landslides, it is impossible to monitor the landslide hazard through the surface displacement monitoring. As a result, there was no successful warning event during the years of installation of the monitoring system through surface displacement, and the mining leaders cannot make mining decisions based on the monitoring results.

During the period from 2010 to 2014, the State Key Laboratory of Geotechnical Mechanics and Deep Underground Engineering of China University of Mining and Technology (Beijing) was commissioned by Nanfen open-pit iron mine to install 57 sets of "Remote Monitoring and Warning System for Landslide Hazard". In 2000, the "landslide 2010-0731 " and "landslide 2010-0805” were successfully predicted. The warning message was detected 11 days in advance to avoid the economic losses caused by landslides totaling 156.96 million RMB and no casualties. From the end of 2014 to the beginning of 2016, there were no artificial disturbances on the slopes of the Nanfen open-pit iron mine due to the decline in the supply and demand of iron ore in China. During the period of time, the monitoring curve of Newton force showed horizontal characteristics and the slope had not changed significantly. In July 2016, with the national iron ore market picking up, No. 3 and No. 4 mining projects resumed. After nearly 4 months of engineering disturbance, the "landslide 2016-1101" occurred at about 3 o'clock on the night of November 1st, 2016 with the influence of winter freezing and thawing alternation. In this landslide, the Newton force monitoring point issued a long-term monitoring and early warning 1 month ahead and issued a temporary warning 4 hours ahead, as shown in Figure 1.4 and 1.5.

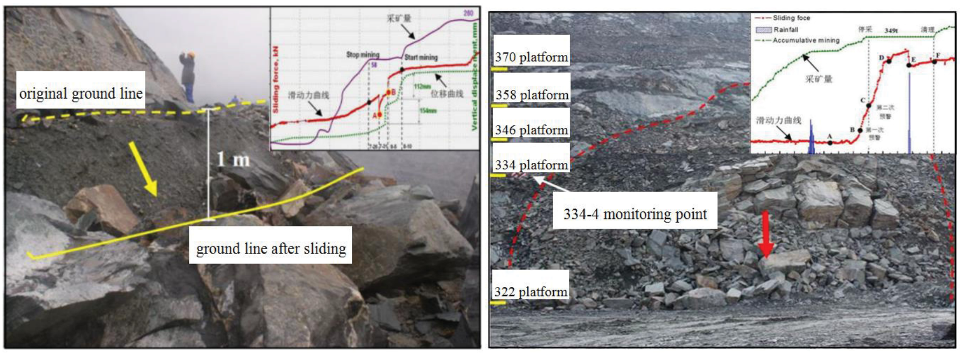


Fig. 1.4 Example of Successful Landslide Prediction

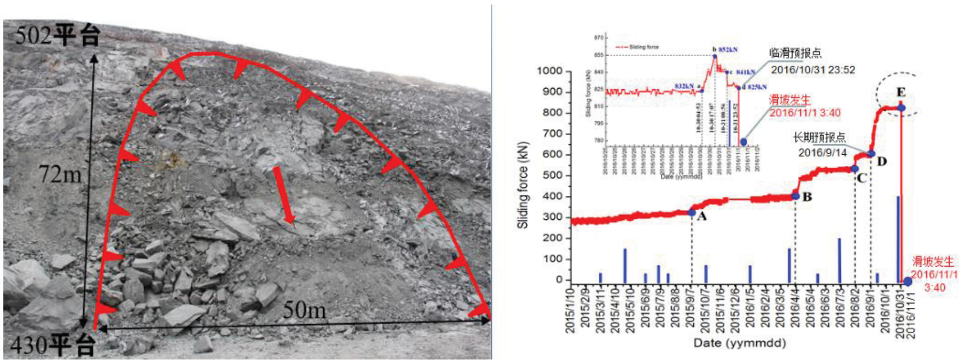


Fig. 1.5 Critical Sliding Warning of "Landslide 2016-1101" in NanFen Open-pit Iron Mine

The research on the monitoring and early warning of the whole process of the landslide based on the Newton force remote monitoring and early warning system has been indicated in numerous literature. However, the study of the Newton force in the whole process of landslide and the numerical simulation analysis still need further study. In this paper, the field geological phenomena was analyzed based on the results of field monitoring data in the "landslide 2016-1101" and the numerical model of constant resistant and large deformation cable is constructed based on Fish language. 3DEC software is used to carry out numerical simulation analysis of Newton force monitoring in the "landslide 2016-1101" to reproduce the whole process of early warning of typical landslide in Nanfen open-pit iron mine. This result will lay a theoretical foundation for the future layout and stability evaluation of Newton monitoring points in iron mine.

1.2 Research contents

Based on the multidisciplinary theory of similarity ratio, rock mechanics, engineering geology and mathematical statistics, the relationship between the physical phenomena of the slope instability and the characteristics of the Newton force change and the surface displacement are studied using the field engineering geological survey and numerical simulation in this paper. The numerical model of the large deformation and failure of landslide is explored and the numerical simulation of large deformation and Newton force characteristics in the whole process of landslide is carried out. This result can be used to form a numerical simulation method of landslide deformation failure based on the monitoring data of Newton force in field. The main research contents are as follows:

(1) Investigation and analysis of the whole process of landslide monitoring in Nanfen

Through the regional geological survey of Nanfen open-pit iron mine, the characteristics of topography, stratigraphic lithology, geological structure, hydro geologic, structural fissure development and spatial distribution of Newton force monitoring points are analyzed. And the mechanism of landslide in the lower platform of the iron mine is studied.

(2) Numerical simulation of the "landslide 2016-1101" in Nanfen

In order to analyze the problem in the process of numerical simulation of landslide deformation by using the existing software, Fish language is used to construct the numerical calculation model of NPR landslide monitoring cable. 3DEC5.2 is used to get the numerical simulation results of the "landslide 2016-1101" and the working conditions in the numerical simulation is designed to match the field conditions to ensure the consistence as much as possible.

(3) Comparison of the field and numerical results of landslide in Nanfen

The deformation characteristics of different parts of the slope, including the top, middle and bottom part, are obtained in the field investigation of the collected data. With the comparison of the field data and the numerical simulation results, the optimal design of the parameters is carried out to simulate the whole process of landslide, which provides the basis for the stability evaluation of other landslides.

1.3 Organization of the thesis

In order to study the change law of the Newton force and propose the simulation model of the whole process of landslide in Nanfen open-pit iron mine, the multidisciplinary theory of rock mechanics, engineering geology and mathematical statistics is used to form a new method to evaluate the slope stability, which combines the numerical simulation results and field data. The research technical route is shown in Figure 1.6.

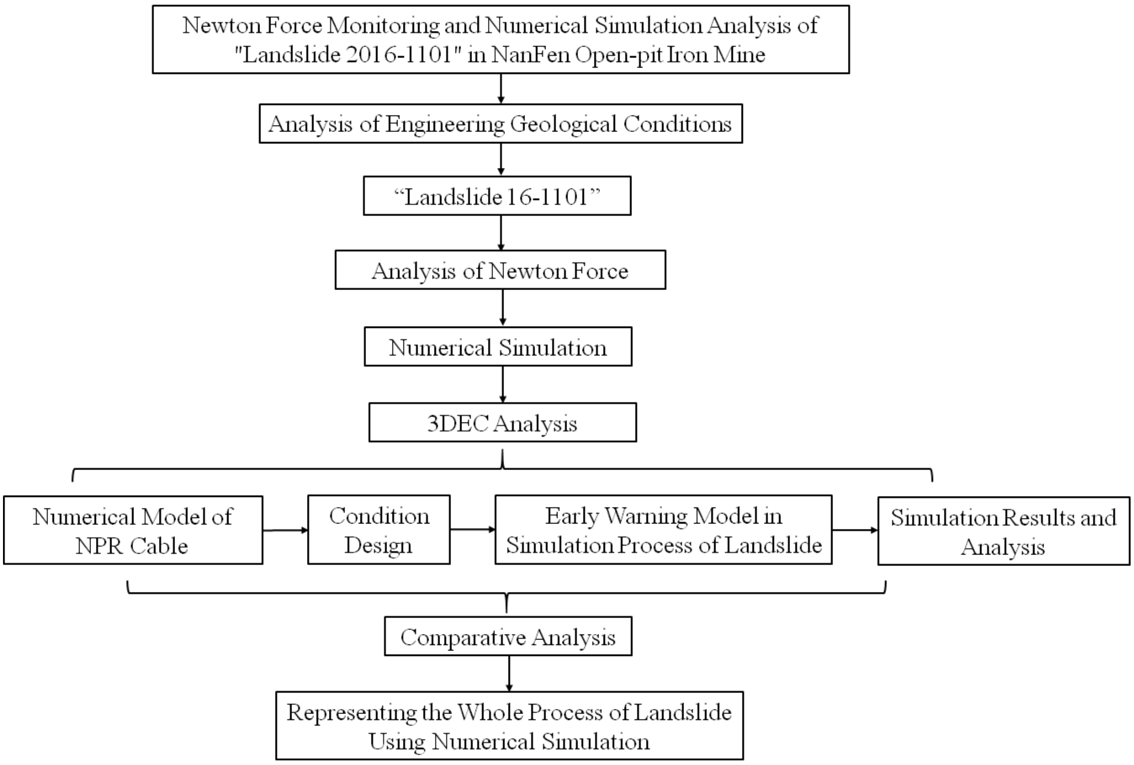


Fig. 1.6 Research Technical Route

Chapter 2 Literature Review

It has been a research problem during last decades to reduce casualties and property losses caused by landslide disasters and forecast the disasters effectively, and the key point of the reliability and authenticity of the forecast results lies in the timely and accurate monitoring and simulation of the data. Based on the analysis of domestic and foreign literature, the research status of landslide monitoring methods and the numerical simulation methods of landslide in open-pit mine are summarized, and the methods to solve the problems are put forward in this chapter.

2.1 Monitoring method of landslide in open-pit mine

The study of landslide monitoring methods is the most basic aspect to improve the effectiveness of forecasting results. The most widely used methods, including deformation monitoring, physical field monitoring, water monitoring, and external trigger factors monitoring, are discussed in the next section.

2.1.1 Deformation monitoring

The contents of deformation monitoring can be divided into two aspects: external deformation and internal deformation. And according to the monitoring method, deformation monitoring can be divided into shallow displacement and deep displacement monitoring as follows.

(1) Shallow displacement monitoring method

Paolo et al. [38] proposed a new method for real-time monitoring of surface displacement induced by landslides called ADVadvanced dIsplaCement monitoring system for early warning (ADVICE), i.e., an advanced displacement monitoring system for early warning. CHOON, SUNWOO et al. [6] analyzed the slope displacement in Basel coal mine in Indonesia monitored by the GPS system, and established the GIS model combined with the fuzzy theory and analytic hierarchy process (AHP). Gang, Zhao et al. [63] used absolute and relative positioning methods to test the factors that affect the accuracy of open GPS positioning, and proposed the static relative positioning accuracy of GPS single frequency receiver in minefield. Ding, XL et al. [8] reviewed the slope monitoring geotechnical instruments commonly used in the Australian open-pit mining industry and then introduced an automatic slope monitoring system based on the integration of electronic geotechnical instruments with specialized software. Hartwig, Marcos Eduardo et al. [14] used DInSAR technology to monitor the surface displacement of N4W iron mine in northern Brazil to conduct a preliminary assessment of its theoretical deformation behavior. Mirtova, I. et al. [35] used remote sensing methods to monitor dangerous exogenous processes and analyzed the dangerous exogenous process dynamics in East-Beysky coal mine using aerial and spatial images taken at different times. Michelini, A. et al. [32] proposed an advanced data processing chain capable of simultaneously measuring a wide range of deformation rates across four orders of magnitude, from very fast movements (up to 150 mm/h) to very low displacements (several mm/month), which can be applied to support the traditional system based on a wide range of long-term monitoring.

There are several types of monitoring methods for shallow displacement listed below.

1) Simple trace observation

Surface phenomena are observed artificially in simple trace observation, including surface cracks, building deformation and this method is also widely used in the steady-state monitoring of slope. At the same time, the surface phenomena and results can be collected and analyzed by the instrument to study the changes in the law and its interaction with the surrounding environment, which play an important role in the highly developed modern society. The simple trace observation method is shown in Figure 2.1.

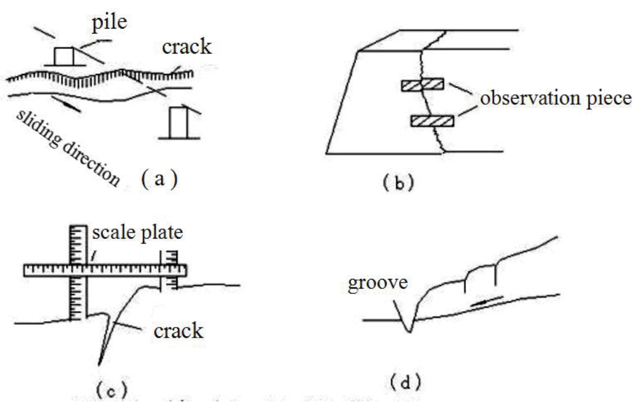


Fig. 2.1 Simple Landslide Monitoring Device

2) Station observation

This method is used to observe the fluctuations of slope in a long and stable period of time by using a theodolite and other geographical observation equipment.

(2) Deep displacement monitoring method

1) Drilling observation:

The main equipment in drilling observation is the drilling inclinometer as shown in Figure 2.2. Fan, G. et al [12] analyzed the application of drilling inclinometer in a highway section of combining Yangtze River quasi-platform. Zhang, L. et al. [59] studied the use of a drilling inclinometer in the geotechnical engineering of the right side of a highway in Guizhou.

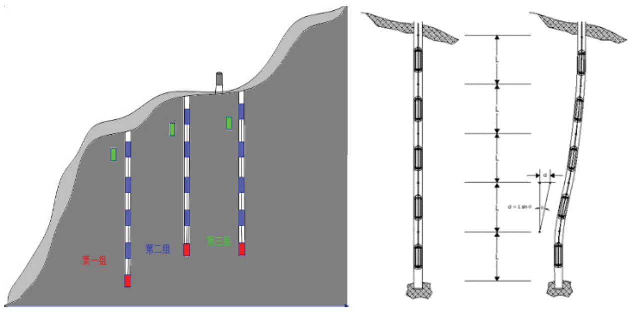


Fig. 2.2 Drilling Inclinometer

2) Time Domain Reflectometry (TDR):

Wu, X. et al [48] analyzed the working principle of each detection instrument used in radar detection technology and proposed the idea of intelligent monitoring system. Tan, H. et al. [44] studied different waveforms in the same shear deformation conditions with TDR monitoring techniques. The operating principle and monitoring curve of TDR is shown in Figure 2.3.

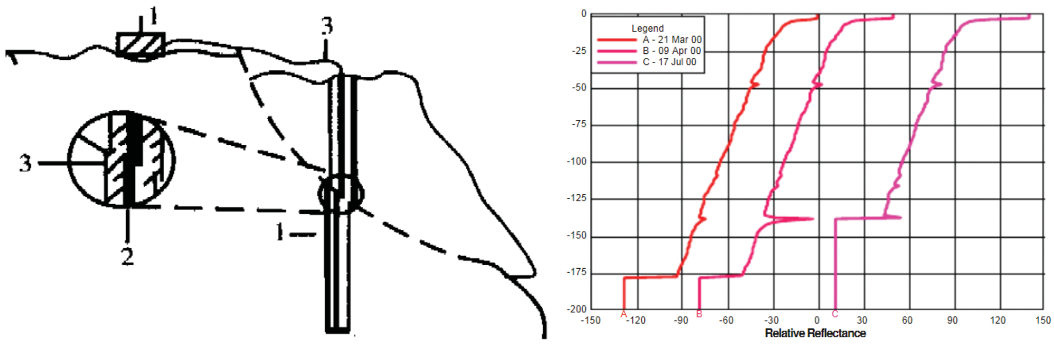


Fig. 2.3 Working Principle and Monitoring Curve

3) Optical Time Domain Reflectometry (OTDR):

The OTDR method is used as a time domain reflection method in fiber measurement. Jiang, S. [20] analyzed the laboratory model tests of rock fall and engineering samples of creep landslide monitored in loess plateau. In this paper, the Bragg grating monitoring system is constructed and applied to the geological hazard of the slope.

2.1.2 Physical field monitoring

The properties of physical field in slope can be monitored in certain ways, including stress field monitoring, acoustic emission signal monitoring, and Newton force monitoring. And the commonly used instruments are anchor stress gauge, anchor strain gauge, vibrating earth pressure gauge and ground stress test equipment.

(1) Ground stress monitoring

Stress monitoring methods can be divided into two kinds: hydraulic fracturing method and stress relief method.

1) Hydraulic fracturing method.

As early as 1957, Hubbert et al. had reported the relevant results of the theoretical study of hydraulic fracturing. And this method is widely used because it can measure thousands of kilometers below the ground easily and can be applied to a variety of geological conditions, which make it the preferred method of work for domestic and foreign geological workers. Cai, M. et al. [2] used the hydraulic fracturing method to analyze the stress distribution of the corresponding location of the deep rock mass in the iron mine area.

2) Stress relief method.

This method is applied to measure the change of stress and strain and other parameters in the instantaneous or slow release process of stress loaded on rock. Chen et al. [4] discussed the advantages and disadvantages of the model comparing with other theoretical models. Yang, R. et al [54] analyzed the field data of several mines by stress relief method and studied the influence of relevant factors on the accuracy of this method. The theoretical results were applied to Zhangji coal mine to improve the driving speed.

(2) Acoustic emission monitoring

The acoustic emission in rock mass has been widely used in geological engineering. The internal storage of the elastic energy will be released in the form of acoustic emission when the rock mass breakdown under loading. Yu et al.[57] studied the causes of the acoustic emission signals in the high-slope rock mass and summarized the variation law of the acoustic emission signal during excavation, which indicates that the slope rock mass is in steady state. Li, J. et al. [22] achieved continuous and real-time automation monitoring of rock mass based on the fluctuation trend of acoustic emission data.

(3) Newton force monitoring.

He, M. proposed the Newton force monitoring method in 2004, which makes use of the NPR constant resistance large deformation material as stress transmission cable, and combine the wireless remote monitoring and early warning system. This method and its related equipment have been applied in a number of large mines in the country. There is a variety of factors resulting in the destruction of a slope and the Newton force is a key factor in these. When the Newton force exceeds the critical value, the rock and soil will collapse and then evolved into a landslide hazard. However, researchers cannot directly measure the Newton force so far, which makes a serious obstacle to the accurate forecast of landslide disasters. He proposed the "2+1" model and solve the unpredictable problems of Newton force in slope successfully. The so called "2+1" model is a combination concept of "natural mechanics system", "artificial mechanics system" and "Newton force", which can achieve the indirect solution of Newton force. We call this method "puncture perturbation" technology and it can be used to make a new complete mechanical system containing man-made mechanical system and natural mechanics system using this technology.

2.1.3 Other monitoring methods

(1) Hydraulic field monitoring

According to the experiment and the site monitoring, it is found that the water has a great influence on the slope stability. The monitoring of the hydraulic field includes the monitoring of the precipitation, the surface and the groundwater. Rainfall monitoring: At this stage the telemetry automatic rain gauge and siphon rain gauge are generally used to monitor the rainfall amount and the technology has been mature after years of use and improvement. Surface water monitoring: Surface water monitoring includes dynamic changes in geological indicators associated with slope rock mass. Observation methods are divided into artificial observation, automatic observation, and remote sensing observation. Groundwater monitoring: The main contents are the groundwater level, rock and soil gap between the fluid pressures, moisture content and so on. The pore water pressure gauge and nuclear magnetic resonance technology are used for detection.

(2) External trigger factors

Landslide-induced factors are generally including earthquake, freeze-thaw and some other geological factors. These factors are usually monitored by the vibration monitoring method, which includes seismic monitoring system and the professional networks of blasting vibration. Cai, L. et al. [3] analyzed the amplitude and feedback information of the vibration signal generated by to reduce the impact of blasting in mining face of Daye iron mine.

2.2 Numerical Simulation of landslide in open-pit mine

The numerical simulation analysis of geological disasters has drawn significant attention in last decades in the field of slope engineering research. A variety of calculation methods and software systems have emerged, such as FLAC, UDEC, PFC, 3DEC, Geo-slope and so on. Researchers have used these methods to carry out a series of simulation studies on slope failure and have achieved numerous research results [33, 34, 47]. Landslide is a continuous dynamic process, which contains disintegration, cracking and accumulation. In the traditional experience of statistical methods, the landslide block model and the two-dimensional particle model, there are some defects, including the applicability of empirical parameters, the problem of motion path, the change of friction in motion, the deformation of sliding body and the problem of erosion entrainment. With the continuous improvement of computer and numerical simulation technology, the numerical method has been developing rapidly in landslide. In addition, the visualization technique of numerical calculation results makes the numerical model more abundant and intuitive. A series of numerical methods for different types of slippage are developed, such as finite difference FDM, finite volume FVM, etc., as well as the establishment of model and methods of numerical control, like discrete element (DEM), discontinuous deformation (DDA), DAN, smooth particle flow (SPH), particle flow program (PFC), tsunami (Tsunami Ball), etc. [49]. In this paper, we focus on the development and research status of finite difference method, discrete element and finite element method (FDEM) in numerical simulation research.

2.2.1 Finite Difference Method (FDM)

Finite difference method has been widely used in mathematical and physical analysis and related simulation software. Maihemuti et al. [30] made numerical simulation analysis on the deformation process of reservoir bank rock slope and use the FLAC3D 4.0 program as the calculation and analysis tool to analyze the deformation mechanism of E20 bank slope. Yang et al. [55] compared the finite difference method and the traditional isotropic coupling model in the problem of rock slope stability by taking into account the characteristics of the anisotropy of the layered rock to indicate that FDM is more feasible and effective. Li et al. [23] studied the three-dimensional numerical simulation of the slope by combining the C++ programming technique with the finite difference method by analyzing the soil slope structural parameters based on the unified strength theory. Xue et al. [51] modeled the protection process of coal pillars in open underground composite mining and FLAC3D was used to simulate the coal pillars with width of 400m, 375m and 350m respectively. The stress and deformation curves of slope were studied and the slope stability factors were proposed.

Based on the numerical simulation method, the three-dimensional numerical model and the seepage model of the landslide process were established by Cheng [5]. The coupling model of seepage and stress field in non-seepage flow mode was used to transform the seepage field of the Ranfang landslide under different calculation conditions into water table face data file in FLAC3D and establish the numerical simulation method for the Three Gorges typical bank slope. Tang, L. [45] used the numerical simulation results of FLAC3D and theoretical analysis methods to establish a warning standard. Yan et al. [53] used FLAC3D as a carrier to establish a numerical simulation model of internal and external causes of landslides with high accuracy. Hu, J.[18] analyzed the whole and local stability and deformation mechanics mechanism of Jiuli landslide with FLAC3D. The simulation results were analyzed comprehensively with the actual deformation monitoring results of Jiuli landslide to validate the harmfulness of Jiuli landslide in this area.

Qi, S. [39] evaluated the mechanics performance of the slope under various working conditions by using the red-plane projection method and the rigid-body limiting equilibrium method. Xu, D. [50] proposed the shear strength model of moraine soil under triaxial loading by numerical simulation and interchangeable use of cellular automata and FLAC3D software. The effect of the excavation process on the stability of the surrounding rock mass is analyzed by Li, S. [24], using FLAC3D for three-dimensional flow-solid coupling analysis. According to the engineering geological conditions, Huang, R. [19] used FLAC3D to simulate the deformation and failure of bedding rock slope and analyze its deformation mechanism.

Yong, R. [56] used FLAC3D to establish a numerical analysis model of the process of landslide and discussed the process of force instability in attenuation coefficients. Zhang, X. [62] simulated the stress field and deformation process of the Xiapa landslide with 3D-Sigma and FLAC3D method. Li, X. [25] proposed a new comprehensive model to predict the structural stability of rock and soil. Yang et al. [55] demonstrated that the proposed model for successful application in the case study was more feasible and effective than the traditional isotropic coupling model used in layered rock slope stability, considering the anisotropy of the layered rock. Zhang, P. [60] analyzed the stress and strain state of the ore structure and rock mass in Antaibao mine, and constructed the numerical model of the slope stability and the visual model under three-dimensional coordinate axis. The FLAC3D software used in this paper is based on the principle of finite difference.

2.2.2 Discrete Element Method (DEM)

Discrete element method can be applied to the simulation of landslide motion. Deng, M. [7] used two kinds of three-dimensional numerical simulation methods, including three-dimensional discrete element method (3DEC) and continuum mechanics discrete element method (CDEM), to analyze the landslide pattern and influencing factors. Dong, H. et al. [9] studied the physical and chemical parameters of the rock and its corresponding mechanical data of the rock test, and used 3DEC to simulate slope changes. Shan et al. [40] discussed the mechanical properties of the slope with 3DEC based on the rock slope treatment project at K56+356 of Zhuanggai Expressway. He et al. [16] obtained a more consistent calculation result and simulation result by comparing 13 calculation examples, proving that it was feasible to use 3DEC method to do simulation. Zhai, C. et al. [58] used 3DEC to simulate the failure mechanism and process of weak base slope, which proved the relationship between the development of cracks and the load. Duan, H. [10] used 3DEC to simulate the slope and calculated the safety factor of high and steep rock slope. Zou, J. [64] took advantage of the discrete element (UDEC) to simulate the failure process of the No. 14 tunnel, and the results showed that under the heavy rain condition, the collapse damage appeared firstly in the lower part, followed by the upper rock falling, which resulted in a kind of layer by layer deformation. Meng et al. [31] discussed the joint development, stress distribution and deformation characteristics of rock in the inlet slope of Changdian Hydropower Station by using 3DEC method, and then evaluated the potential failure mode and stability partition of the rock mass in the early stage of blasting. Li et al. [26] integrated numerical simulation results and GB-InSAR monitoring data to analyze the landslide case of Fushun open-pit mine and proposed the discrete element method based on continuums. The deformation characteristics, failure mechanism and evolution of large open slope with typical anti-process were analyzed. PFC (Particle Flow Code) [28] was an analysis program of particle flow developed by the ITASCA company based on the discrete element method, divided into PFC2D and PFC3D.

The above discrete numerical simulation method is based on solid mechanics theory, while not suitable for analysis of slope process or recovery of existing landslide. In this paper, we simulate the dynamic process under loading with the discrete element method. When the blocks move, including slip, rotation, fracture and so on, the change of slope state during the excavation process can be simulated according to its macroscopic discontinuity.

2.2.3 Finite-Discrete Element Method (FDEM)

The traditional continuous numerical methods have been widely used in the simulation research and their practicality and validity have been fully confirmed, especially for the finite element method and boundary element method [15, 21, 27, 41, 42]. However, the continuous methods can only simulate the small deformation before the failure of the slope, while the discrete element method can be used to realize the modeling of the internal cracks coupling the multi-physics fields in rock and soil. But this method cannot simulate the cracking of rock and slope under external disturbances [52] and is powerless for the whole process of cracking, expansion, penetration, detachment, slip (or rolling), collision and accumulation in rock and soil.

In view of the above problems, some scholars have begun to explore the coupling method of continuous and discontinuous methods to achieve numerical simulation of the material instability and crushing in slope and rock [1, 11, 29, 36]. The most representative one is the hybrid method of finite element and discrete element method (FDEM), which establishes a bridge between continuous and discontinuous methods [37]. However, due to the extremely complicated process of slope failure and the poor stability and reproducibility of the basic physical and mechanical parameters of slope rock, the simulation results are not in good agreement and reliability. In order to solve the problem, the numerical model of landslide can be established by FDEM method, followed by contrast and optimization about the simulation results by comparing with the monitoring data of GPS surface displacement system and field failure characteristics. And the parameters can be adjusted step by step to ensure that the calibration of fault parameters and the scale of fault rock can reflect the real process of landslide. This method provides a reference for similar non-continuous methods to study slope cracking.

FDEM is the abbreviation of finite element-discrete element method. Munjiza combines the finite element method which is suitable for continuous analysis and the discrete element method which is suitable for discrete analysis, such as transient, contact detection and contact interaction, to propose a powerful tool for mining and large-scale slope failure [37]. The computational grid of the FDEM method is realized by the usual finite element discrete technique. The planar problem is solved by using a triangular element to connect the four nodes on the two sides of two adjacent triangular elements to form a four-node cohesive unit.

In the simulation process of slope cracking and failure, there is need to introduce other macro-destruction criteria in the calculation process because the progressive damage of the rock material is realized based on the strength passivation of contact units (fracture unit) when the cohesive element model is used, which can be regarded as an inevitable destruction in the deformation process. If the cohesive unit is broken, the corresponding crack-containing element is removed from the continuous calculation model so that the model locally achieves the transition from continuous state to discontinuous state. The fracture models include two types: 1. Torsional failure and 2. Shear failure, which are in fact the combination of single and passivated crack models. In the calculation process, the displacement and rotation of discrete element body are allowed and the new contact is automatically recognized by the calculation program. In the solution process of the discrete system, the displayed integral format is used to update the cell node coordinates at each time step after convergence.

2.3 Problems to be solved

Although there are various techniques and equipment for landslide disaster monitoring and early warning, as well as the numerical simulation methods applied to projects, the following problems are existing in landslide monitoring methods and technical equipment because of improper selection of monitoring parameters and methods:

(1)When rock and soil are under loading and the internal balance state between material intersection changes, i.e., the "Newton force" reaches the limiting value of rock and soil, landslides occur. In the previous study, people focused on the physical indicators such as the displacement or the nature characteristics of rock and soil, while the "Newton force" is not analyzed and discussed thoroughly, leading to inaccurate prediction of geological disasters.

(2)In the current monitoring systems for landslides, the disaster analysis is limited to small-scale or small deformation and it cannot be used to monitor the whole process of landslides, neither effectively analyze the large deformation. The main drawback is that the material responsible for the transmission of stress and strain properties in the previous monitoring system belongs to a small deformation material, which means the material itself cannot meet the requirements of large deformation in the slope. When rock and soil deformed under loading, the material used to transmit the mechanical properties has been inevitable damaged, resulting in that the entire monitoring system cannot work. The simulation model of landslide based on the previous material is also a small deformation model, and it cannot simulate and calculate the large deformation of landslides accurately. It is necessary to use new mechanical materials on the landslide monitoring and early warning system to improve the accuracy.

(3)The traditional monitoring equipment cannot be used to monitor the "whole process of landslide. When a landslide occurs, the surface displacement and the internal mechanics in rock changed greatly. However, the traditional monitoring equipment of displacement and stress are destroyed and the monitoring function is lost due to the large deformation of the rock and slope.

(4)The existing software can only simulate the small deformation before the failure of slope because of the flaw of the algorithm. And the discrete element method has realized the modeling of joint and fissure with considering the complex conditions of multi-physics, but it cannot be used in the simulation of large deformation, such as the slope rock cracking, expansion, penetration, detachment, slip (or rolling), collision and accumulation of the whole process, because this method cannot simulate the cracking in slope under the external disturbance.

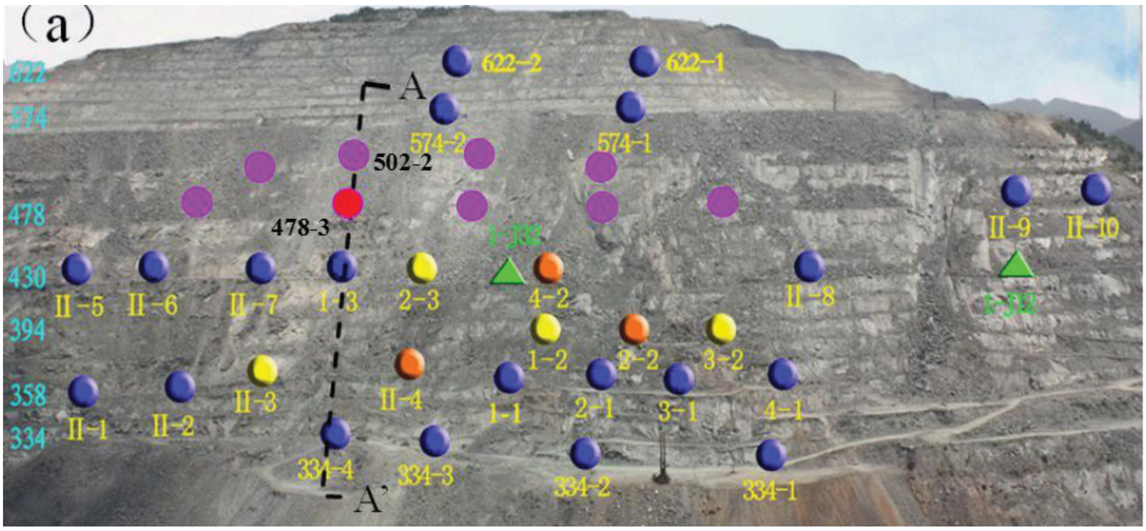
In view of the above problems, it is discussed and analyzed the changing law of the Newton force in the whole process of landslide in this paper, and carries on the numerical simulation to form a new method to evaluate the slope stability by combining the numerical simulation in the whole process with the field data.

Chapter 3 Analysis on the Whole Process of "Landslide 16-1101" Monitoring and Early Warning

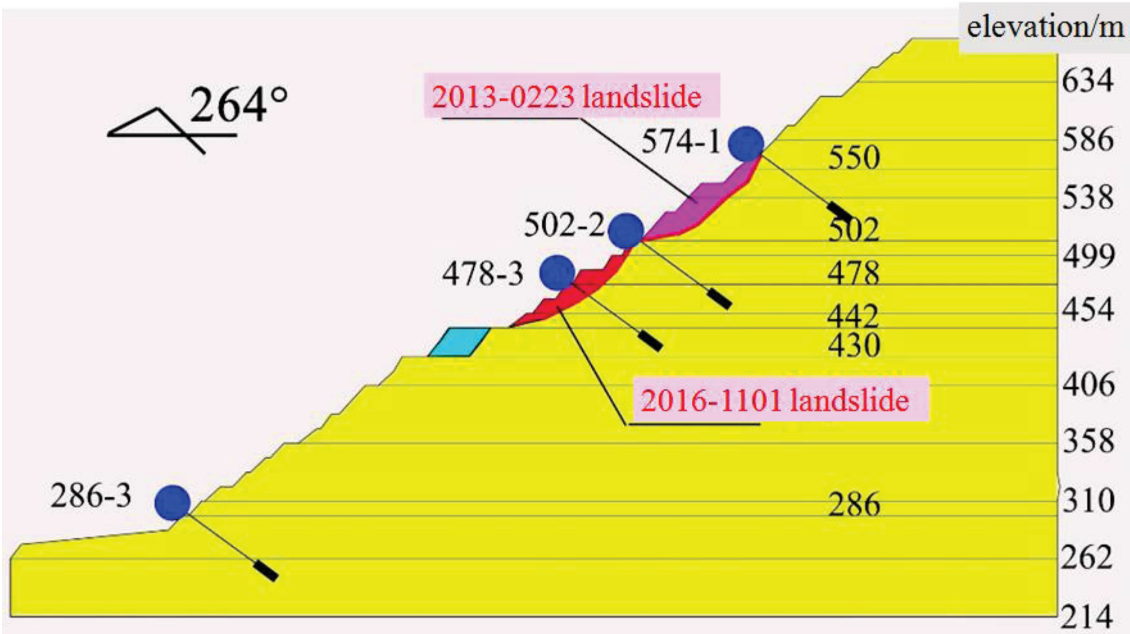
3.1 Monitoring points design

In June 2015,according to the outcrop feature of the final slope footwall of Nanfen open-pit iron mine and the structural characteristics of the old landslide body, 9 deep sliding force monitoring points are added in the new design on the landslide body (478-502 m steps).The buried depth is 55-84 m, incident angle is 45°, the azimuth is 84° and the data acquisition frequency is designed as f=1/hour [46].Constant resistance large deformation cable (referred to as: NPR cable) which has negative Poisson's ratio properties is used in all the sliding force transmission device.

In November 2015, all monitoring points began to work properly. The dots in Figure 3.1 (a) represent the deep sliding force monitoring points (The new nine monitoring points is marked as purple dot), the green triangle represents the original surface displacement GPS monitoring point, and Figure 3.1(b) shows the cross-sectional feature of the monitoring area along the A-A 'section line.



(a)Distribution characteristics of monitoring points



(b)Sectional view of A-A’ in the monitoring area

Fig.3.1 Distribution of monitoring points and section characteristic

3.2 Warning level

According to the four color-coded early-warning criteria of red, orange, yellow and blue established by He Manchao [17,46,61],combined with the demand for time of on-site equipment evacuating the danger zone and practical operability, long-term warning, medium-term warning and critical sliding warning levels were established. As shown in Table 3.1.

Table 3.1 early-warning criteria

warning levels	danger level	early-warning interval/kN early-warning threshold/kN	curve characteristics
long-term warning	mildly dangerous	250-350 300	sudden rise
medium-term warning	dangerous	550-650 600	sudden rise
critical sliding warning	extremely dangerous	N1-N2 ΔN	sudden drop

(1) Long-term warning: When the sliding force of the sliding force monitoring curve slowly increases by T∈[250 kN，350 kN](early warning value T = 300 kN), and the monitoring curve appears phenomenon of sudden increase, the system will issue a

"long-term warning" automatically. It requires monitoring personnel to strengthen monitoring and report step by step in form of "daily statements";

$$T=Tn-T_0 \tag{1}$$

Where:

T - sliding force increment, kN;

Tn - the latest sliding force monitoring value, kN;

T_0 - preload value when the equipment is initially installed, kN.

(2) Medium-term warning：When the sliding force of the sliding force monitoring curve slowly increases by T∈[550 kN，650 kN](early warning value T = 600 kN), and the monitoring curve appears phenomenon of sudden increase, the system will issue a "medium-term warning" automatically. It requires evacuation of working personnel and large equipment in danger areas, and setting warning signs on the roads in danger area;

(3)Critical sliding warning: When the sliding force of the sliding force monitoring curve suddenly reduces, the amplitude T=N and N≥20 kN, the data are regarded effective, and it can be ruled out that this change is caused by system errors or signal interference. As the monitoring curve appears phenomenon of sudden drop, the system will issue a "critical sliding warning" automatically. The whole staff (including monitors and investigators) and small equipment must be all evacuated from the danger zone and all roads to the danger zone must be blocked.

$$N=Nn-Nn-1 \tag{2}$$

Where:

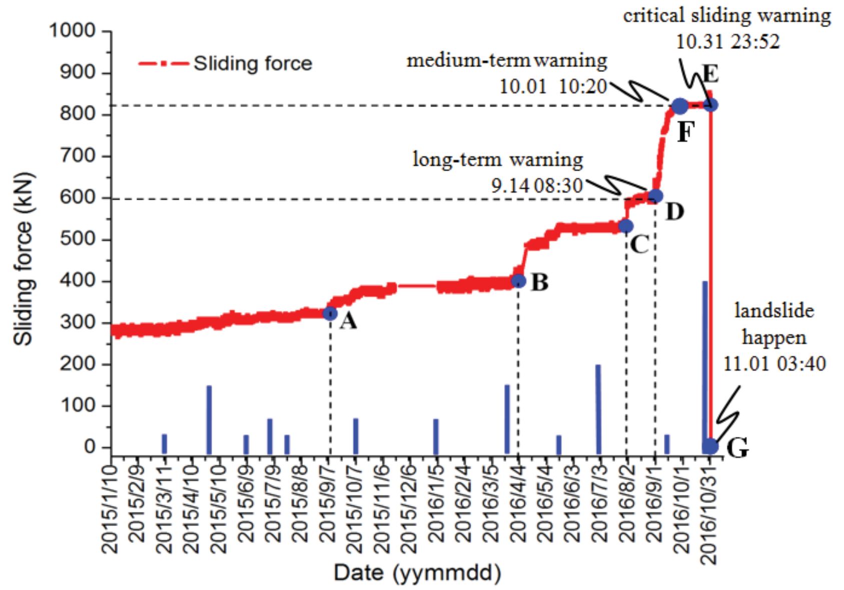
N——Absolute value of the sudden drop of sliding force，Positive value，kN；

Nn——Sliding force monitoring value when the sudden drop ends，kN；

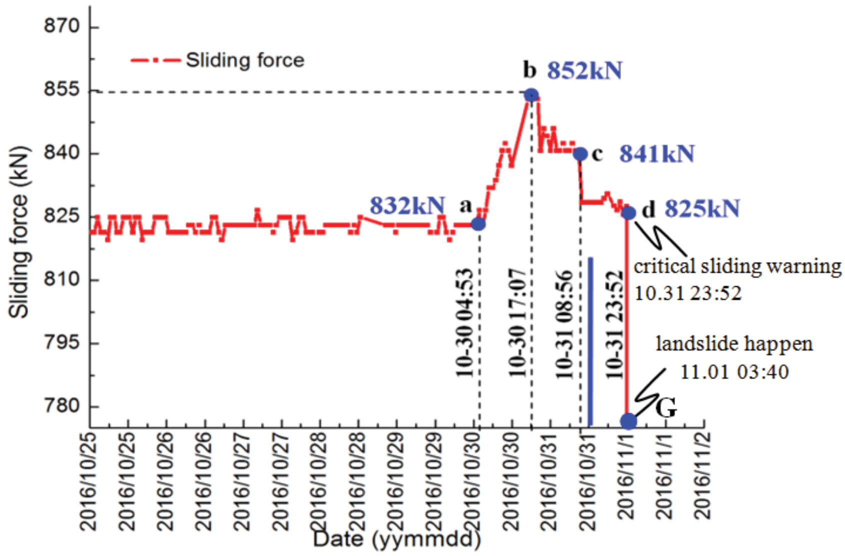
Nn-1——Sliding force monitoring value when the sudden drop begins，kN。

3.3 Analysis of deep sliding force monitoring results

After nearly 12 months of continuous monitoring, tens of thousands of precious monitoring data are received. According to the newly established landslide warning criteria and threshold, from October to November in 2016, the NO.478-3 monitoring point of the system issued a long-term forecast 45 days ahead of the Nanfen open pit iron mine "landslide 2016-1101 ", issued a medium-term forecast 30 days in advance, issued a catastrophe warning within the scope of the whole mine 4 hours in advance. The monitoring curve is shown in Figure 3.2.



(A) NO.478-3 monitoring curve



(B) Partially enlarged of point ”E” of NO.478-3 monitoring curve

Fig.3.2 Coupling monitoring curve

Figure 3.2 shows the monitoring curve of the whole process of "landslide 2016-1101" and early warning process in Nanfen open-pit iron mine stope footwall:

(1) NO.478-3 monitoring curve rises slowly before September 14, 2016. Even if there are many sudden increases such as point A, point B and point C, the incremental amount is less than the warning threshold. According to the newly established warning level, the incremental is less than the warning threshold, that is, T <300 kN, and the system did not issue any warning information. Through field investigation, due to the

large number of large diameter pumice piled up on the slope, it could not be observed whether there are cracks in the surface;

(2) At 8:30 on September 14, NO.478-3 sliding force monitoring curve increases faster. After reaching point D, the cumulative increment T> 300 kN, and the system issued a "long-term warning" message in the pre-set small range of early warning personnel(monitoring center technician and mine leadership).Through field investigation, it was seen that there isn't significant deformation and cracks on the surface. Mine decision-making layer required increasing of the monitoring frequency in the region and set it to f = 2 / hour;

(3) At 10:20 on October 1, NO.478-3 sliding force monitoring curve is flat. But when it reaches point F, sliding force cumulative increment T> 580 kN, and the system issues a "medium-term warning" message in the pre-set small range of early warning personnel. Through field investigation, it was found that there was an electric shovel stripping rock directly below 430 m step. The straight line distance is about 48 m between the operating point and NO.478-3 monitoring point. Surface cracks were not significant. Mine decision-making layer required all large-scale machinery and the slope expansion personnel to evacuate the scene. Data acquisition frequency was set to f = 4 / hour;

(4) At 23:52 on October 31, NO.478-3 monitoring curve suddenly drops (point E).The system issued a "critical sliding warning" message in the pre-set wide range of early warning personnel (all the staff below the stope, monitors and mine leadership). Mine decision-making layer took emergency measures, and required all the safety personnel and monitoring personnel in danger area to evacuate. As the time of critical sliding warning information is short, it cannot be identified in the whole curve. Therefore, the range of point E in Figure 3.2 (a) is partially enlarged and a partial enlarged curve is obtained as shown in Fig. 3.2 (b). As can be seen from Figure 3.2 (b), the sliding force value of point d has suddenly dropped 27 kN, so a "critical sliding warning" message is issued. Data acquisition frequency was set to f = 6 / hour;

(5) At 3:40 on November 1, on-site monitoring station on the hanging wall reported landslide, accompanied by two loud noises, and a large number of rolling stones rolled along the slope and accumulated on the 430 m step. There is a dislocation of about 3.5 m on the trailing edge of the landslide body. The destruction characteristics of the top of slope after landslide are shown in Figure 3.3.

Fig.3.3 Characteristics of the top of “2016-1101” landslide

As the "landslide 2016-1101" was pre-warned timely and evasive measures are taken decidedly, it did not cause any casualties and property damage.

3.4 Landslide cause analysis

(1) Accumulation loading on top of “landslide 13-0223”

After “landslide 13-0223” occurred, about 4 *104 m^3 (weight 11.4 *104 t) of loose rock accumulated in the 502m step over the years and hadn’t been cleared until “landslide 16-1101” occurred. Therefore, accumulation loading on top of the slope is an important external cause of secondary “landslide 16-1101”.

(2) Slope foot expansion disturbance unloading

On September 14th, 2016, the roller-bit hole rig on 442m step is operating at a distance of about 150 m below the monitoring point, and has small disturbance to the area. On October 30th, 2016, the 17# electric shovel on 430m step is carrying out excavation operations from north to south at just 20m below the NO.478-3 monitoring point. Therefore, the excavation and unloading of slope is the main cause of the secondary “landslide 16-1101 ”.

In summary, slope foot unloading and accumulation loading on top of slope double disturbance, resulting in “landslide 16-1101 ”.

Chapter 4 Numerical Simulation Analysis of Landslide Based on 3DEC Software

4.1 Design of simulation phase

Based on the above analysis, there was a landslide in February 2013 on 502m-550m slope above the 16-1101 landslide body, and after nearly three years of accumulation loading, it has been in a relatively stable state. In addition, because the main cause of “landslide 16-1101” is the excavation and unloading of slope on 430m step, so this simulation is divided into two stages to analyze:

(1)13-0223 landslide body accumulation loading stage: Simulation of a large amount of loose deposits loading at the top of the 16-1101 landslide body after the “landslide 13-0223 ”happened, accelerating the expansion and penetration of the sliding surface;

(2) 16-1101 landslide body foot excavation unloading stage: Simulation of using mechanical excavation disturbances to produce unloading rebound at 430m platform.

In order to realize the numerical simulation of large deformation of landslide, the mechanical model of NPR cable with the function of constant resistance and large deformation is established for the first time using the Fish language in discrete element software 3DEC5.2, and numerical modelling and analysis are conducted for "landslide 16-1101 ".

4.2 The large deformation design principle of of NPR cable in 3DEC

In general, the cable reinforcement unit in 3DEC5.2 is defined by geometric parameters, material parameters and anchoring agent properties. Since the cable member is elastoplastic. Therefore, the "one-dimensional constitutive model" can be used to describe its axial characteristics, the axial stiffness K is expressed as follows:

$$K = \frac{AE}{L} \tag{3}$$

Where:

K-cable axial stiffness, N / m;

A-reinforced cross-sectional area, m^2;

E- elastic modulus of cable, GPa

L- cable length, m.

In practical application, the parameters "tensile yield strength Ft" and "compressive strength FC" of the cable can be specified according to the engineering background in 3DEC5.2, but the parameters set in the constitutive model cannot exceed these two limits. Thus, once the geometry of the cable is determined, there are only two types of keywords of elements left that control the cable member, namely, "tension" and "anchoring agent parameters (gr_coh, gr_fric, gr_k, gr_per)". As the failure mechanism of conventional small deformation cable is because that it does not have the characteristics of constant resistance and large deformation, so it will inevitably produce minor deformation damage or anchoring agent failure when the tensile strength is exceeded.

On the contrary, for the NPR cable that has the characteristics of constant resistance and large deformation, the same anchorage strength properties as the ordinary bolt/cable is set at the end of anchorage section of the NPR cable by fish language in the modeling process of 3DEC5.2; At the end of the free section of the NPR cable, that is, the anchor nodes, it is set to be rigid contact with the slope rock mass and simulate the actual anchor effect. The working principle of large deformation is as follows: When the axial force (axial tension or shearing force in the axial direction) applied to the NPR cable reaches the design constant resistance value P0, there is axial tensile deformation in NPR cable immediately; When the deformation reaches the design elongation (including the elastic deformation of the cable), the anchoring agent is considered to be invalid, and the anchor unit is released, thus reaching the set large deformation effect. In the process while cable is working, use fish language to set parameters and determine the elongation of NPR cable, and monitor its axial force variation characteristics in the meantime.

Based on the above large deformation design principle, using the program in 3DEC5.2, the NPR cable model with "constant resistance and large deformation characteristics" has been developed. The model and its static tensile mechanical properties are shown in Fig4.1.

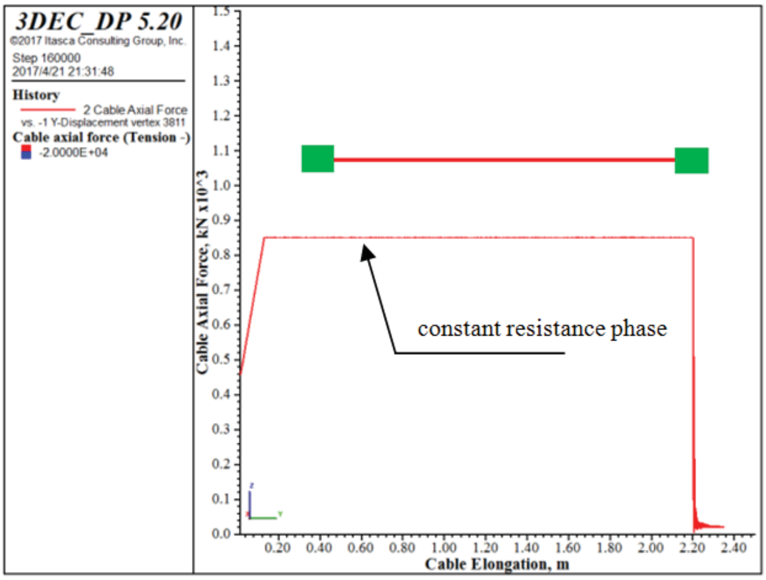


Fig. 4.1 Numerical anchor model and its static mechanical feature

4.3 Model building and meshing

The maximum width of both 13-0223 landslide body and 16-1101 landslide body is 50 m, and the height boundary of the two landslides are 502 m-550 m and 430 m-502 m, respectively. Considering that the width of model boundary need to be greater than 2.5 times the width of the target body, the model elevation is set as 277 m-634 m, and width is set as 200 m. In order to simulate the spatial relationship between the upper and lower slide bodies, the contact surface element is arranged between the sliding body and the rock base, so that the interface characteristic during the sliding process can be simulated. The rear, bottom and sides of the landslide are respectively set as fixed boundary, and the upper and front sides of the landslide are set as free boundary. The boundary of 13-0223 landslide body and 16-1101 landslide body and boundary of the expansion and excavation area is shown in Figure 4.2. The main rock mechanics parameters are set as shown in Table 4.1. The cable structure parameters are shown in Table 4.2.

Tab. 4.1 Parameters of rock mechanics

Rock Name	volume weight (kg/m^3)	bulk modulus (GPa)	shear modulus (GPa)	cohesion (kPa)	frictional angle(°)	Tensile Strength (MPa)
Rock Base	2900	40	18	420	36	1.5
Sliding body	2500	20	8	70	27	0.2

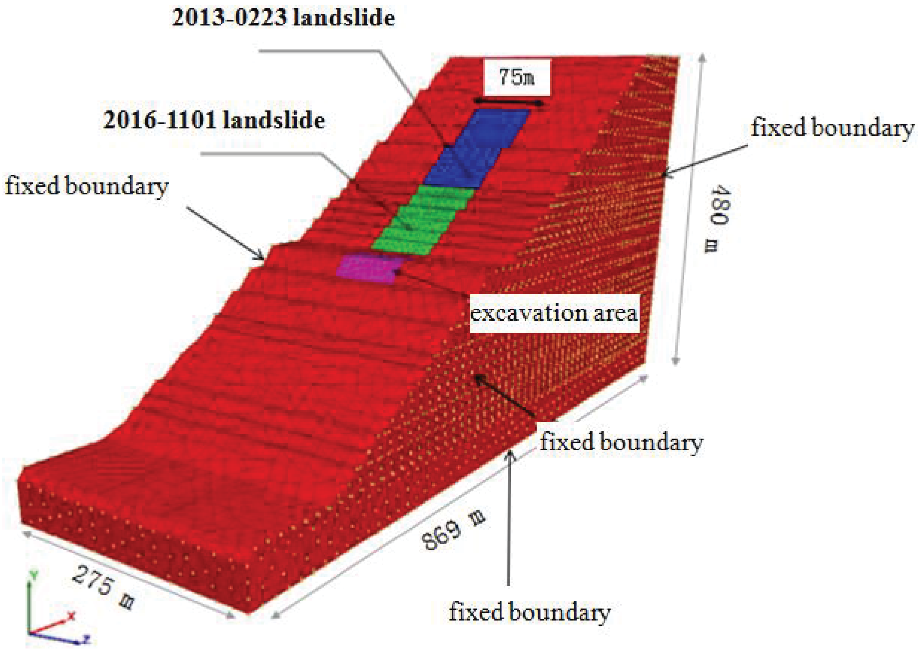


Fig. 4.2 Model establishment and meshing

According to the point coordinates of the deep sliding force monitoring point and depth parameters of NPR cable, the NPR cable module is constructed in the model, its parameters are: Inclination is 30 °, length is 75 m, preload is 400 KN, and constant resistance is 850KN (Table 4.2). In addition, the excavation length of the electric shovel at 430m step is set as 70 m.

Tab. 4.2 Parameters of Anchor

NPR cable	length (m)	inclination (°)	preload （KN）	constant resistance(KN)
	75	30	400	850

4.4 Simulation results analysis

(1) “Landslide 13-0223” numerical simulation results analysis

3DEC is a discrete element software of block simulation analysis based on discontinuous medium mechanics, the Lagrangian algorithm, Newton's second law and force displacement law are used to analyze the mechanical response of blocks and structural planes.

The elastic-plastic model based on molar coulomb yield conditions is used in this simulation. Observing the sliding surface displacement contour, subsidence volume observation curve, as well as cable axial force monitoring curve, when the subsidence curve does not change, it is determined that the slope has reached a steady state. On the contrary, continue to calculate. According to the above principles, after numerical calculation, the maximum displacement of "landslide 13-0223" after stabilization is 1.2m. The landslide body is basically located in the set position of model contact surface. When the landslide starts, the contact surface strength is set as the actual sliding surface strength, then slip until the steady state. Due to the reinforcement of a number of cables with constant resistance and large deformation, the “landslide 16-1101” didn’t disintegration sliding integrally, only in the tongue portion there is crushing failure mode, and tensile failure in the central portion and the trailing edge. As shown in Figure 4.3.

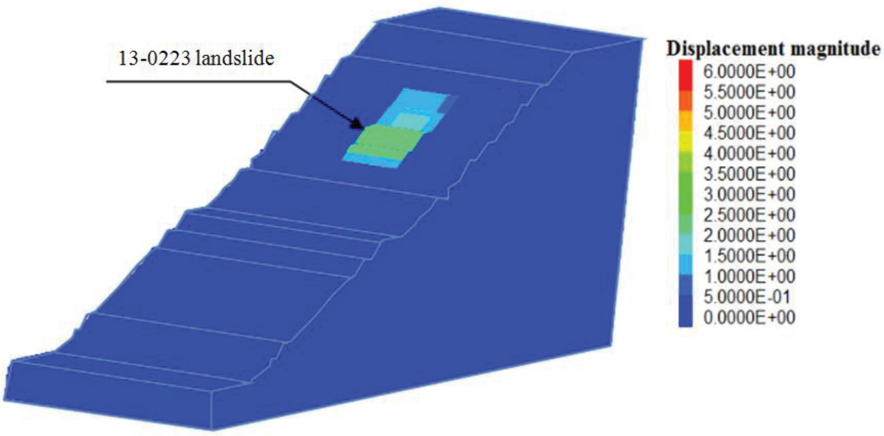


Fig. 4.3 Displacement contour of “landslide 13-0223”

(2) “Landslide 2016-1101” numerical simulation results analysis

Before the slope foot excavation calculation of 2016-1101 landslide body, firstly cleared the deformation and speed of “landslide 13-0223”, fully considered stacked loading effects on landslide 16-1101, and then start the operation program. The results are shown in Figure 4.4.

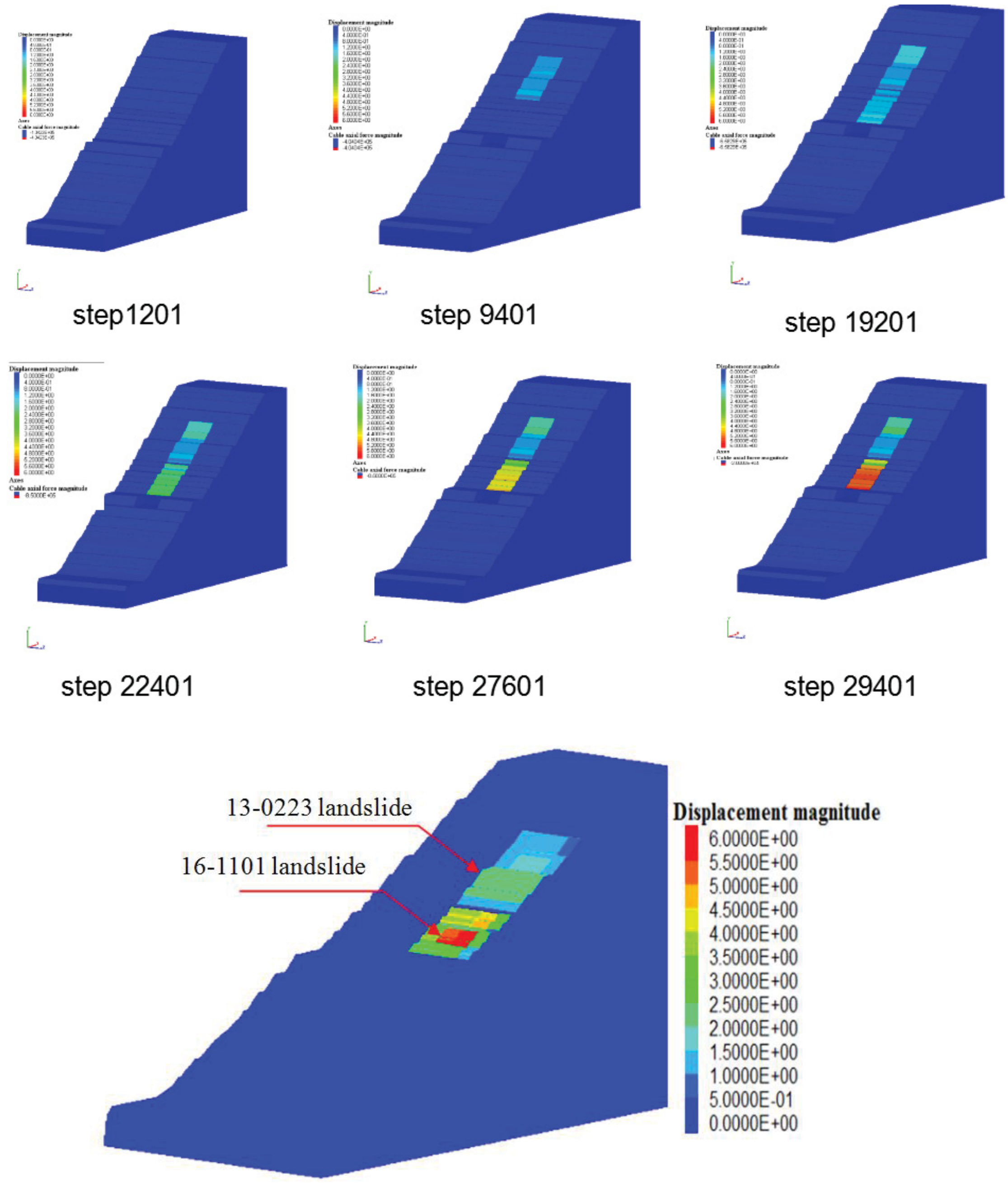


Fig. 4.4 Displacement contour of “landslide 16-1101” by 3DEC

"landslide 16-1101" is a secondary landslide started after the upper 13-0223 landslide body was stable. Figure 4.4 shows the displacement change contour and the final displacement contour of "landslide 16-1101". In this simulation process of slope destruction, it is a process of slow and phased strength degradation from stability to complete instability of the 16-1101 landslide body. No matter it is slope foot excavation or other factors, the direct cause of instability is the continuous weakening of the sliding surface, that is, the sliding surface is completely deteriorated and the strength is reduced to insufficient to support the entire sliding body.

Therefore, in the actual calculation, the strength of the contact surface (slip surface) should also be step weakened until rock mass instability. The staged parameters of the contact surface strength from steady state to the last sliding state are shown in Table 4.3.

Tab. 4.3 Strength degradation stages criteria

stage	normal stiffness /GPa	shear stiffness /GPa	Cohesion strength /KPa	frictional angle /°
first	9	14	148	21
second	9	12	36	20
third	9	10	25	19
fourth	9	8	18	18

After "landslide 16-1101" started, the axial force variation feature of NPR cable which is set in the middle of 478 m step of the sliding body is shown in Figure 4.6 (a). Figure 4.6 (b) is the cable elongation curve. Figure 4.6 (c) shows the vertical relative displacement curve of the monitoring point on the upper edge of the "landslide 13-0223 ". Figure 4.6 (d) is the vertical relative displacement curve of the monitoring point on the upper edge of the "landslide 16-1101". Among them, the monitoring point on the edge of "landslide 13-0223" and the monitoring point on the edge of "landslide 16-1101" are corresponding to monitoring point 1 and monitoring point 2 in Figure 4.5. We can see the following characteristics:

1) Slope foot excavation unloading stage (stage1):

At this stage, electric shovel excavation leads to unloading disturbances on 430m step. The axial force of NPR cable changes from the preload 400kN to 530kN. The elongation of NPR cable reaches 0.3m, and there is a trend of gradually increasing with the reactivation of the old landslide body. Slide produces a relative displacement of 0.6 m. Slide produces a relative displacement of 0.6 m.

2) Reactivation and start stage of 13-0223 landslide body (stage2):

13-0223 landslide body reactivates. The potential sliding surface link up. And the strength of the weak surface in the sliding surface decreases gradually from strong to low. The axial force monitoring curve quickly increases to 680kN, the elongation of NPR cable reaches 0.64m, and there is a relative displacement of 1.54m in the sliding surface.

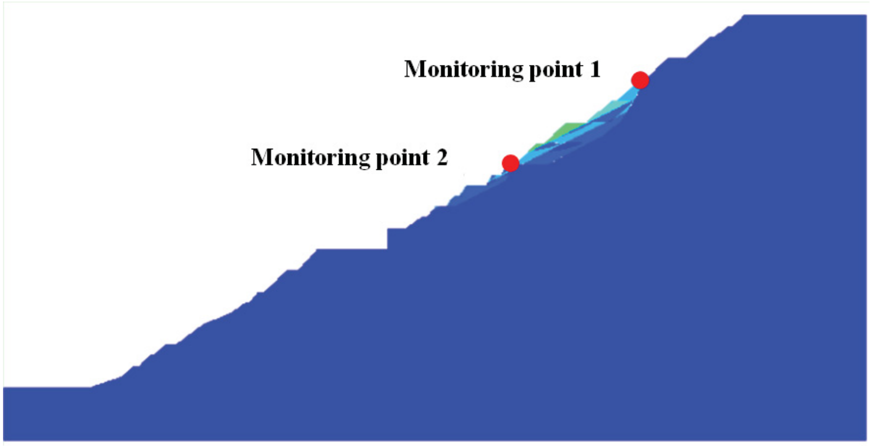


Fig. 4.5 Monitoring points for vertical displacement by 3DEC

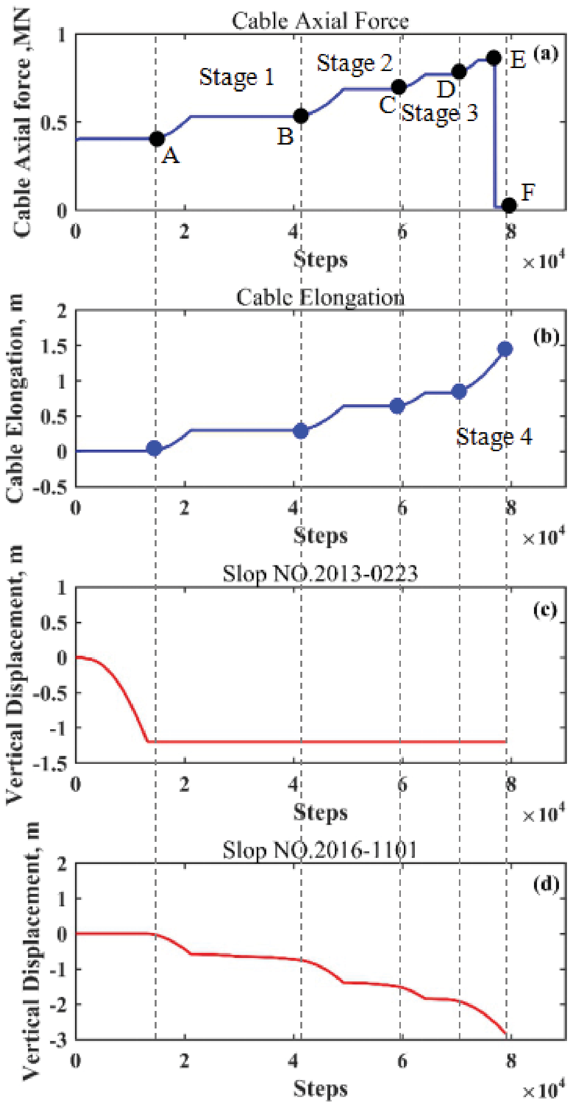


Fig. 4.6 Monitoring curve of “landslide 16-1101” by 3DEC

3) Relative displacement stage 16-1101 sliding surface (stage3):

In this stage, influence of excavation on sliding surface has reached the safety threshold. The axial force of NPR anchor quickly increases to 770kN, the elongation of NPR cable reaches 0.84m, and there is a relative shear displacement of 1.87m of the sliding body along the potential slip surface.

4) Early warning stage of "landslide 16-1101" (stage4):

This stage continues the accelerated trend of stage 3. The axial force continues to rise until constant resistance 850kN. When the relative displacement of the sliding surface reaches 2.54m, the sliding surface completely loses stability and the cable is invalid. Axial force suddenly drops to 18kN, the elongation of NPR cable reaches 1.45m. The system issues early warning information. Typical displacement section contours are selected according to a certain number of steps (Figure 4.7), representing the whole process of "landslide 16-1101" completely.

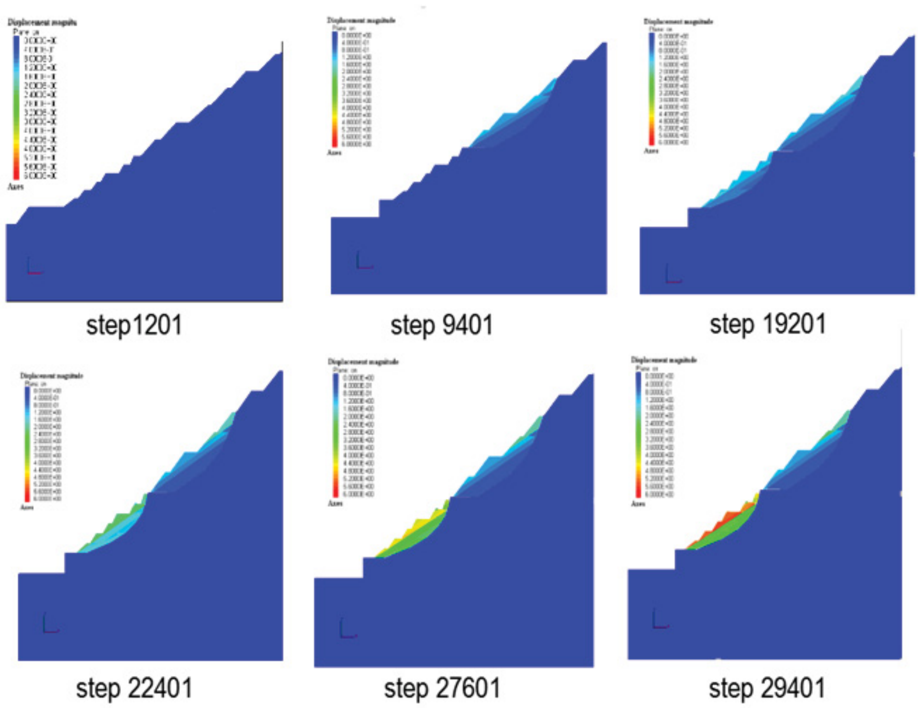


Fig. 4.7 Typical section displacement contour of "landslide 16-1101"

4.5 Comparison of simulation results and on-site monitoring data

The measured parameters are obtained through field investigation. It is found that the actual subsidence of the top of "landslide 16-1101" is about 3.5 m. The central part shows an obvious tension crack deformation zone, and the subsidence is about 12m.

The bottom part is extrusion deformation zone, with an amount of sinking about 2-3m. The slip mass mostly stacked on the bottom 430 platform, as shown in Figure 4.8.

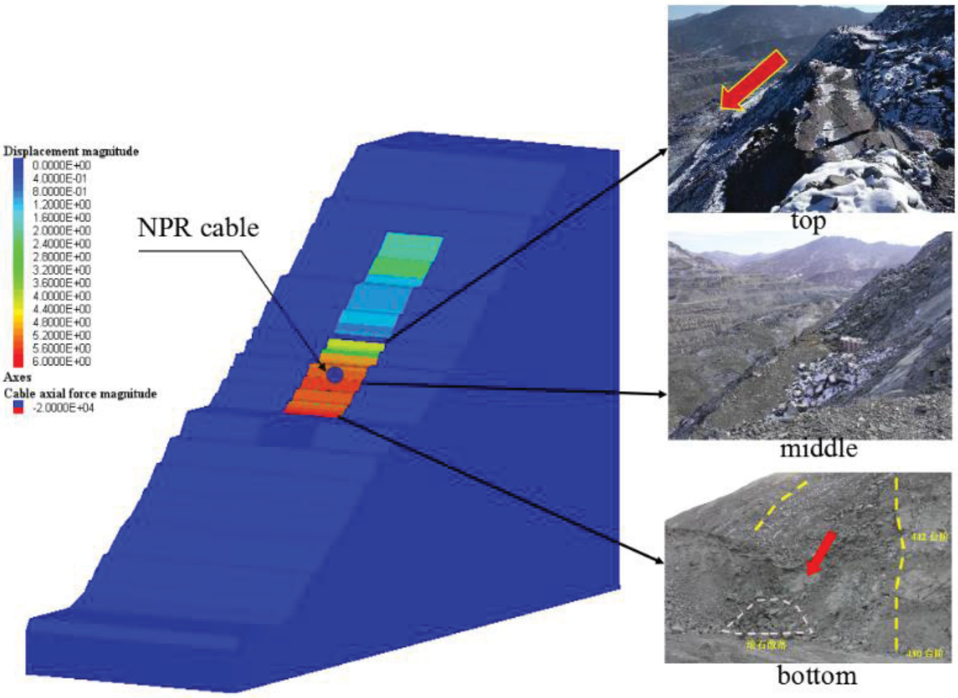


Fig. 4.8 Failure Characteristics

In order to see the monitoring effect, select the 478m step in the sliding body and establish NPR monitoring cable in the middle of it. The axial force change of NPR cable is continuously monitored by numerical simulation calculation after the "landslide 16-1101" started. Its characteristics are shown in Figure 4.9.

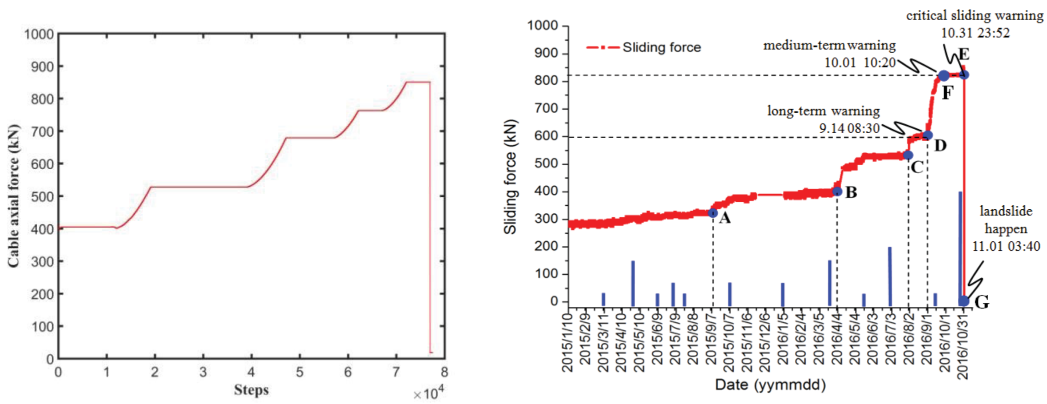


Fig. 4.9 Comparison of Axial force simulation curve and

monitoring curve of NPR cable in landslide 16-1101

Through the comparison of numerical simulation curve and field monitoring curve, it is found that the crack characteristics are obvious. There are four different degrees of cracks before sliding, their trend and linear characteristics are basically consistent. Through the above analysis, it is found that there is a significant consistency between the actual monitoring results and the simulation results which provides theoretical and practical basis for landslide mechanism analysis and numerical simulation of other similar slope.

Chapter 5 Conclusions

In this paper, through the numerical simulation analysis of large deformation failure of "landslide 16-1101" in Nanfen open pit mine, expected results obtained are as follows:

(1) Large deformation numerical calculation model of NPR landslide monitoring cable is established, achieving the goal of large deformation simulation without damage and revealing the large deformation mechanical law of NPR monitoring cable under static load condition in the numerical calculation process.

(2)Applying the numerical calculation model of NPR landslide monitoring cable to calculation using the discrete element software 3DEC5.2, the calculated maximum deformation reaches nearly 6m. The numerical simulation monitoring curve of cable force also shows four increases and one decrease, with the amplitudes of 130kN, 150kN, 90kN, 80kN, respectively, and suddenly drop to 18kN finally. The sliding surface completely loses stability and the cable is invalid. It is consistent with the site monitoring curve, and the numerical simulation of the whole monitoring and warning process of "landslide 16-1101" in Nanfen open pit iron mine is realized.

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