International Core Journal of Engineering Volume 6 Issue 6, 2020
ISSN: 2414-1895 DOI: 10.6919/ICJE.202006_6(6).0029

Analysis and Monitoring Design of the Evolution Stage of Anti-dip Slope in Open-pit Mines——Taking the Slope of the Northern Side of an Open-pit as an Example

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Abstract

Aiming at the problem of anti-dip slope stability monitoring in open-pit mine goaf, taking the anti-dip slope in the north of an open-pit mine as the research object, use the engineering geological analysis method and discrete element numerical simulation analysis method to systematically analyze the slope influencing factors of deformation and failure, characteristics of evolution stage and deformation trend. The results show that the anti-dip slope of the northern side of the open-pit is in a stage of rupture and evolution. On the basis of analysis and study of its deformation failure characteristics and deformation trend, the slope stability monitoring design was carried out.

Keywords

Open-pit mines; Anti-dip slope; Deformation trend; Numerical simulation of discrete element; Monitoring design.

1. Overview of the study area

This open-pit is a super large deep concave open pit coal mine. The mining site is about 6.6km long from east to west, 2.2km wide from north to south, and about 400m deep (Figure 1). The northern side of the open pit mine has a history of large-scale underground mining operations for many years. It is currently in the pit closing stage, and the slope is almost entirely within the scope of the mining disturbance. Due to the special geographical position of the northern slope of the open pit mine, the damage degree and range of geological hazards are large.

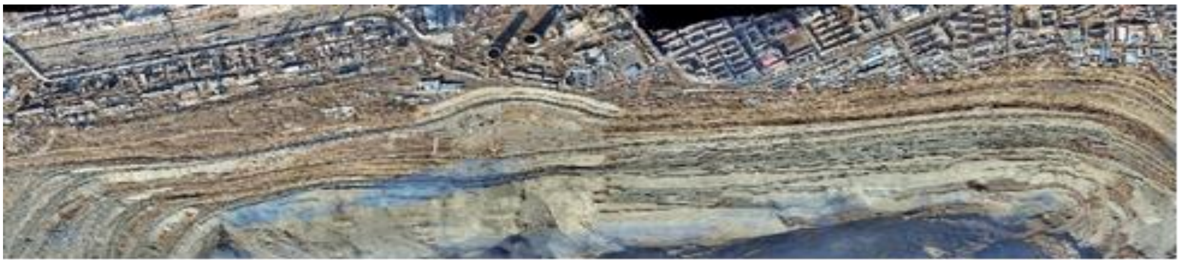

Fig.1 Schematic diagram of north slope

1.1 Geological structure of the side slope

The northern slope of the open pit is in the form of a ring-shaped excavation track plus a side slope. The slope angle is about 30°. The lowest elevation in the east row is -368 meters, the middle is -284 meters, and the west is -284 meters.

The strata affecting the stability of the northern side slope are: Quaternary surface alluvial layer loose rock group, Tertiary soft-hard inter-bedded rock group, Tertiary hard rock group, Cretaceous sand, shale and conglomerate inter-bedded rock group [0].

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The structural planes that have a greater impact on the slope stability are the main fault $F_{1a}$and secondary faults F_1 of the Hun River and the stratum level controlled by fold structure[2]. Three small-scale secondary faults F_{1-1}、F_{1-2}、F_{1-3} have also developed between the fault F_{1a} and the fault F_1(Figure 2).

The fault F_{1a}tends to northwest, with a dip angle of 70° ～75° and a trend of 80° ～85° . The upper wall is basement gneiss system, and the lower wall is Cretaceous basalt, sandstone and sand shale; the fault $F_1$is located on the southern side of F_{1a}, developed parallel to F_{1a}, tending to the north, and the dip angle is 47° ～52° . The upper wall is the Cretaceous Lung Fung Kan Formation stratum, and the lower wall is the Tertiary coal stratum stratum [3].

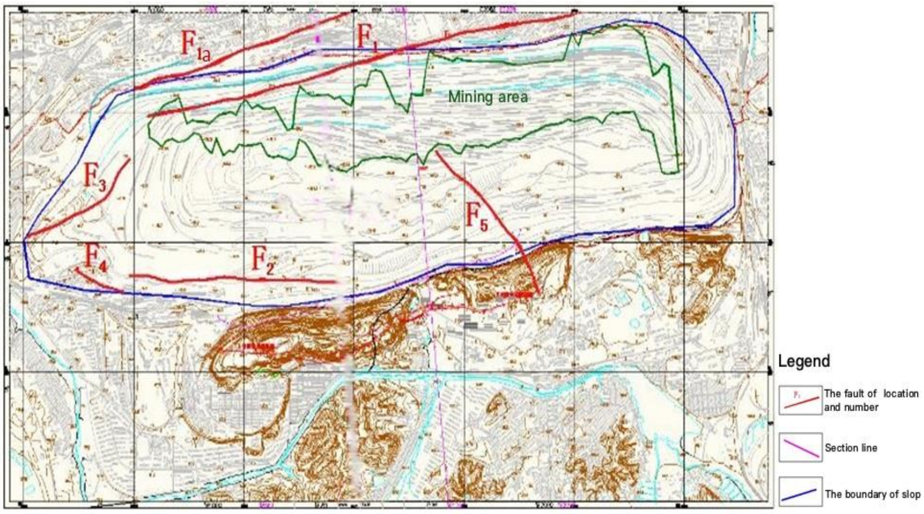

Fig.2 The location of faults[1]

The fold structure mainly includes coal field traction syncline and compound fold. The occurrence of the north wing of the coalfield towed syncline is inverted-upright-sloping at a large angle, and the southern wing is relatively gentle; the compound fold is located in the green mud-stone layer of the south wing of the traction syncline. Three secondary synclines and two secondary anticlines have been developed from east to west.

1.2 Hydrogeological conditions

The mining area is located on the plain between the Hun River in the north and the hilly mountains in the south. The terrain is relatively low. The general trend is slightly higher in the northeast and slightly lower in the southwest. The terrain is gentle and the slope is 2‰. The characteristics of surface water and groundwater in the mining area are as follows:

The surface water system of the northern region includes the Hun River in the north and the Guchengzi River in the west. The Quaternary surface alluvial floor of the north slope is 3-10 meters below the normal water level of the Hun River, so that the slope alluvial layer directly recharge the fixed head of the Hun River, the hydraulic connection is close[3].

The groundwater in the northern area is mainly Quaternary pore water and bedrock fissure water. Quaternary pore diving mainly occurs in gravel and sand layers. The buried depth of the static water level is 6.0-10.0 meters, and the elevation of the static water level is 73.74-74.87 meters. There are three types of fissure aquifers in the northern bedrock, namely gneiss fissure aquifers, Cretaceous fissure aquifers and shale fissure aquifers. The gneiss fissure aquifer is above the fault F_{1a}, and the rock fissure is well developed, with strong permeability; the Cretaceous fissure aquifer is between the fault $F_{1a}$and the fissure F_1, fracture developed; the shale fissure aquifer is above the kerogen shale in the south of the fault F_1. The permeability is smaller in the vertical bedding direction and larger in the parallel bedding direction [4].

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1.3 Mining activities

In the lower part of the northern slope of the mine, the Shengli Mine and deep wells have been underground mining operations for many years. Shengli Mine is located in the lower part of the northern slope, the mining method is mainly the long-wall method, and the water and sand shale is used to fill [5]. Mining began in 1907, stopped in 1979. Early mining depth reached -100 meters elevation, and later mining depth was limited to -420 meters to -650 meters elevation. The deep wells were mined in 1952 and stopped in 1977. The mining depth ranges from -100 meters to -417 meters.

Open-pit mining began in 1914. The mining method of the mine in 1984 was “Zone mining, zone development, combined transportation, internal dumping”, and later adjusted to “Whole zone mining, zone development, combined transportation, internal dumping” [6] . The coal mining method is the open-top coal mining method, and the transportation method is mainly train and car transportation.

The mining loads on the slope of the open pit mine mainly include mine shocks, blasting shocks formed during mining and mechanical vibrations formed during vehicle transportation.

1.4 Natural environmental factors

The mining area belongs to the mid-temperate East Asian continental monsoon climate zone. The main climatic characteristics are hot and rainy in summer, long in winter and cold, large temperature difference and distinct seasons. The rainfall is mainly concentrated from July to September, with an average annual rainfall of 760-790mm.

The mining area is located on the eastern side of the Tanlu earthquake zone, where earthquakes occur frequently. Since the establishment of a seismic network in 1965, the city has monitored 17 earthquakes [7].

2. Analysis of the evolution stage of deformation and failure of the northern anti-dip slope

Using numerical analysis method, combined with the influence factors of slope deformation and failure, the characteristics of slope deformation and failure evolution stage and its deformation trend are analyzed.

2.1 Geological model

The actual situation of the typical formation of the anti-dip slope of the north side of the open pit was reasonably generalized to establish a slope geological model (Figure 3). Model geometry parameters: The model is 1305.3 meters long, 658.6 meters high and 400 meters wide, with an initial slope angle of 28° and a slope height of 339.04 meters. The model considers two large faults and three secondary faults.

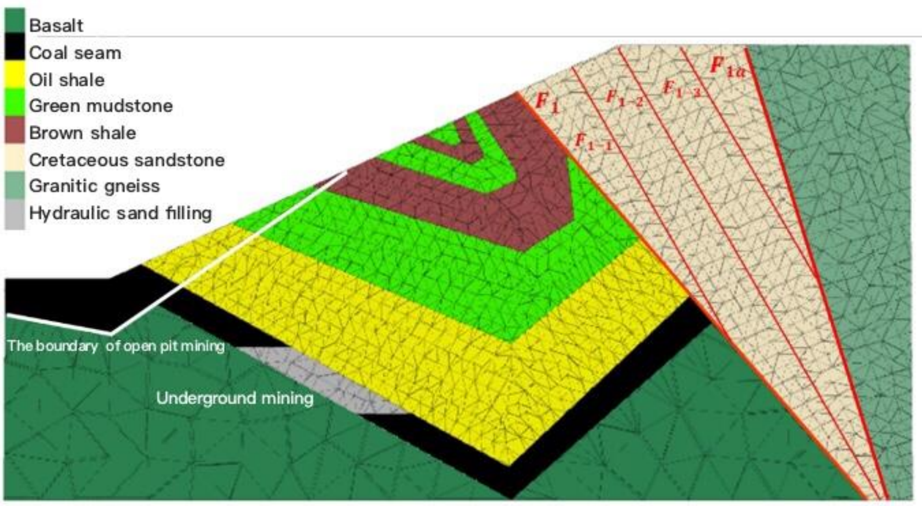

Fig.3 Geological model of mine anti-dipped slope

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2.2 Numerical calculation model

The three-dimensional numerical calculation model is shown in Figure 4. The model adopts a speed constraint boundary, the bottom horizontal and vertical speed constraints are 0, and the lateral horizontal speed constraints are 0. The rock-soil body adopts the ideal elastoplastic mechanical model and the Mohr-Coulomb yield criterion, and the structural plane adopts the Coulomb slip model.

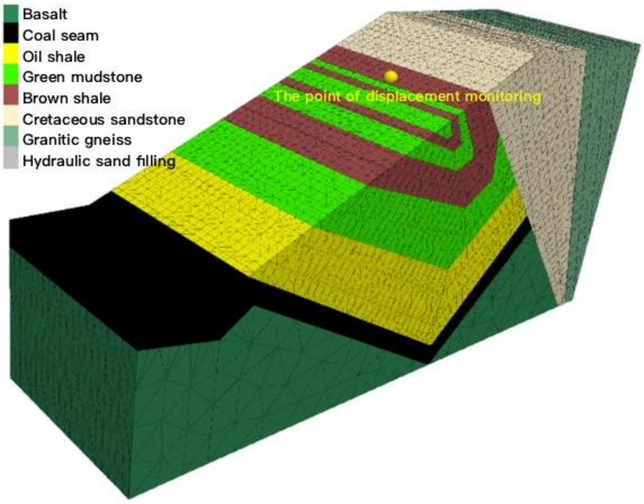

Fig.4 Numeric calculation model of mine anti-dipped slope

2.3 Selection of physical and mechanical parameters

Due to the complex geological conditions in the study area and the diversity of rock lithology, based on long-term predecessors' long-term geotechnical experimental studies on the area, the physical and mechanical parameters of each rock and structural plane are averaged as shown in Tables 1 and 2.

Tab.1 Physico-mechanical parameters of rock mass

lithology	Density/ ($kg \cdot m^{-3}$)	Bulk modulus/MPa	Shear modulus/MPa	Cohesi on/MPa	Friction angle/(°)	Tensile strength/MPa
Kerogen shale	1800	2220	1085	0.6	30	1.8
Brown shale	2250	1480	606	0.6	26	0.32
Cretaceou s sandstone	2300	3330	2000	1.1	29	3
Green mudstone	2250	1480	606	0.5	25	0.22
Coal seam	1300	910	468	0.28	15	0.24
Basalt	2700	15432	10163	2.5	48	2.5
Granitic gneiss	2800	18520	12200	4	54	5
Water sand filling	1500	1110	370	0.05	18	0

Tab.2 Physico-mechanical parameters of rock discontinuities

Structural plane type	Tangential stiffness coefficient/(GPa/m)	Normal stiffness coefficient/(GPa/m)	Cohesion /MPa	Friction angle/(°)
Rock strata	10	10	3	40
Steep structural plane	3	3	0.3	20

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2.4 Simulation scheme design

According to the coal mining activity of the open-pit mine, the simulation scheme design is carried out. The simulation process is divided into three stages: slope natural deformation stage, underground coal seam mining stage, goaf filling and open-pit mining stage. The underground coal seam is excavated 200 meters along the trend, divided into 6 excavations, each excavation 33.33 meters. After the underground mining is completed, water and sand are used to fill the mined-out area, and open-pit mining is carried out on the slope foot area, and the lower slope angle of the post-mining slope is 31° (Figure 3).

2.5 Simulation results and analysis

(1) Natural deformation stage

Under the condition of no mining, the slope body iteratively calculated 21462 steps to reach the initial equilibrium state, and the stress and displacement characteristics are as follows.

Characteristics of stress field in natural state. It can be seen from Figure 5 that the whole slope body is in a state of compressive stress, and tensile stress appears in the slope and local areas of the fault, and the maximum tensile stress value is 1.031 MPa. Under the action of tensile stress, the slope surface rock mass gradually unloads and deforms toward the free surface. When the tensile principal stress is greater than the tensile strength, the rock mass forms tensile failure and unloading cracks occur. The appearance of tensile stress on the slope top and fault area indicates that when the principal tensile stress of the rock mass is greater than the tensile strength, the fault rock mass slides and the ground on the top of the slope cracks, forming ground fissures.

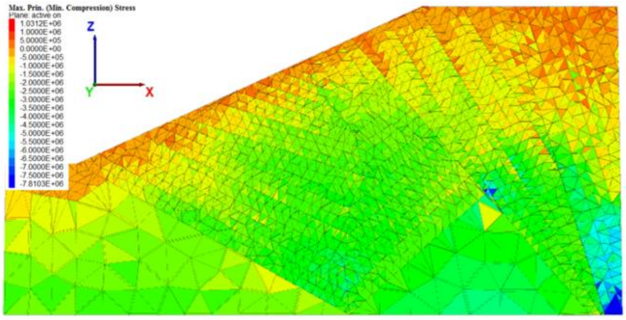

Fig.5 Maximum principal stress nephogram on slope under natural condition

Displacement field characteristics in natural state. It can be seen from Figure 6 that under the action of gravity, the soft rock (oil shale, coal seam) at the lower part of the slope forms compressive creep deformation, and the displacement of the slope body is directed to the soft rock with a maximum displacement value of 0.141 meter. It can be seen from Figure 7 that the north flank of the syncline has a reverse dip structure and a rock layer with a large dip angle forms a dumping deformation with a maximum horizontal displacement value of 0.086 meter.

In the natural state, the maximum displacement of the northern slope is 0.141 meter, no obvious deformation occurs, and the whole is in a stable state.

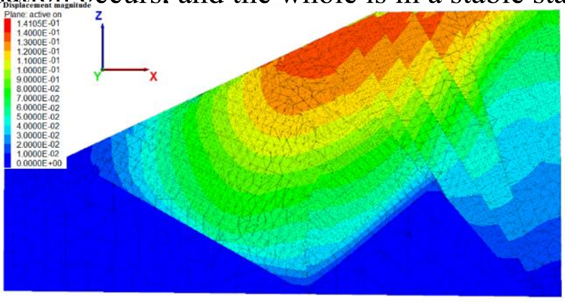

Fig.6 Displacement nephogram on slope under natural condition

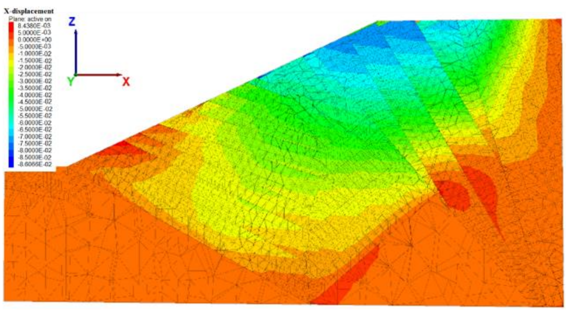

Fig.7 X-displacement nephogram on slope under natural condition

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(2) Underground coal seam mining stage

Characteristics of slope stress field. As shown in Figure 8, with the underground coal seam mining, the internal free surface of the slope continues to increase, the stress is redistributed, and the stress concentration phenomenon occurs in the cover rock in the goaf, indicating that the cover rock in the goaf will gradually form subsidence deformation. The tensile stress distribution range and stress value of the slope and fault local area increased, and the maximum tensile stress value increased by 0.12MPa, indicating that the surface cracks on the slope and the ground cracks on the top of the slope will continue to extend.

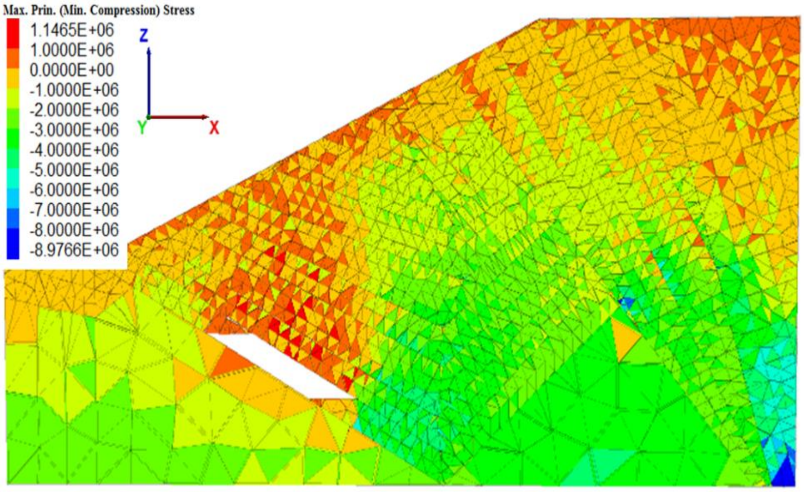

Fig.8 Maximum principal stress nephogram on slope under underground coal mining stage

Slope displacement field characteristics. As shown in Figure 9, the mining of underground coal seam leads to subsidence deformation of the overburden rock in the goaf, and the maximum vertical displacement of the direct roof is 2.54 meters. With the mining of coal seam, the goaf subsidence deformation gradually developed upward, and uneven subsidence appeared on the slope surface. The horizontal displacement of the slope increased sharply, and the maximum horizontal displacement increased by 0.61 meter compared with that when it was not mined, indicating that under the action of underground mining disturbances, the slope's toppling deformation increased (Figure 10).

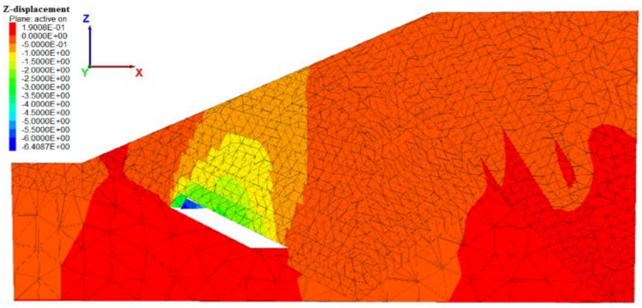

Fig.9 Displacement nephogram on slope under underground coal mining stage

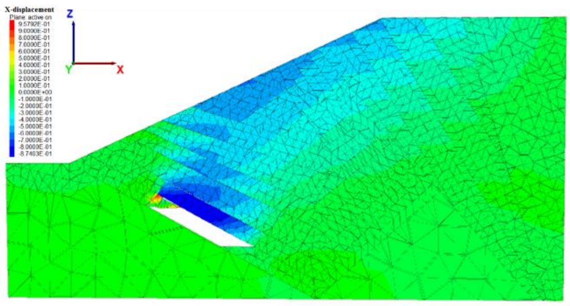

Fig.10 X-displacement nephogram on slope under underground coal mining

(3) Goaf filling and open-pit mining stage

It can be seen from Figure 11 that in the underground coal mining stage, the displacement increment of the slope monitoring point A is 0.471 meter, and after the goaf is filled, the displacement increment of the monitoring point A is 0.115 meter, indicating that the filling of the goaf reduces the rate of slope's deformation. In the open-pit mining stage, the displacement increment is 0.369 meter, and there is no obvious convergence trend in the displacement curve, indicating that the excavation of the slope foot leads to continuous deformation of the slope, and the whole slope is in the stage of rupture evolution. It can be seen from Figure 3-10 that after underground and open-pit mining of the slope, the surface rock mass of the slope has obvious slip deformation, the maximum displacement value is

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1.037 meters, and there is a differential displacement area, which is the potential damage boundary of the slope. It can be seen from Figure 9 that the horizontal displacement at the top of the slope increased by 0.865 meter compared with the time when it was not mined, and the slope continued to deform. A horizontal differential displacement has occurred in a local area on the top of the slope, which is the site of ground fissure development.

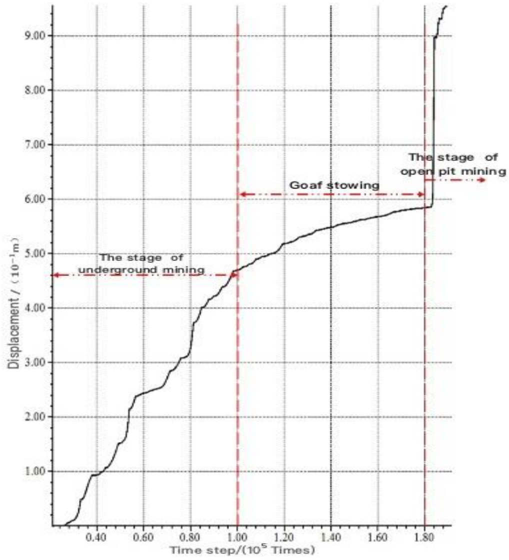

Fig.11 Time–stepping of displacement at monitoring points A on slope surface

2.6 Characteristics and deformation trends of the deformation and failure stages of the northern slope

It can be seen from the analysis of the numerical simulation results (Figures 11, 12, and 13) that the whole north slope is in the stage of rupture evolution. The mining of the underground coal seam redistributes the internal stress of the slope body, the tensile stress of the rock layer is concentrated between the north flank of the syncline and the fault, and the dumping deformation is intensified. The rock strata at the syncline axis lost support and produced slip deformation. Filling of the mined-out area reduces the slope deformation rate. Later, the excavation of the slope foot by open-pit mining changed the free space and stress field of the slope. The deformation rate of the rock mass increased, and the slope continued to slip and deform.

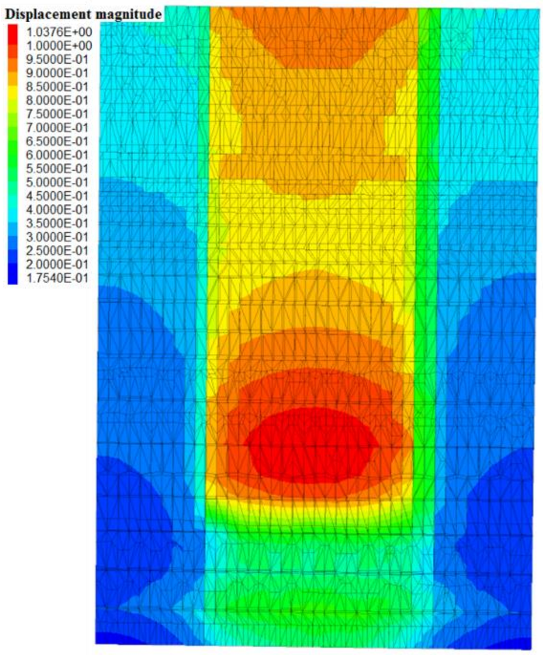

Fig.12 Displacement nephogram on slope surface under open-pit mining stage

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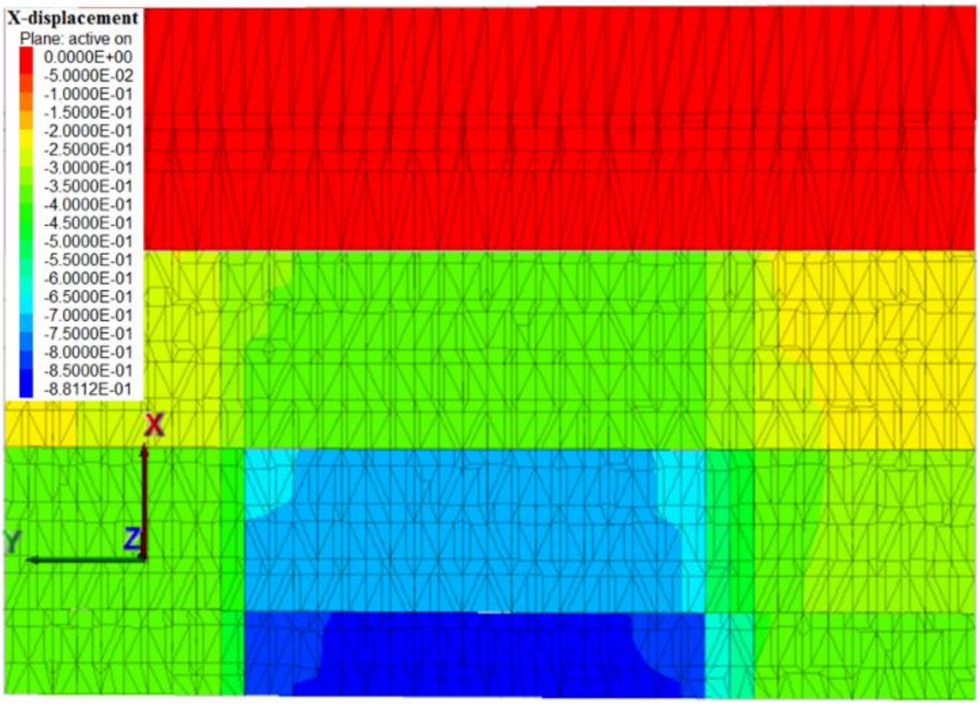

Fig.13 X-displacement nephogram on the top of slope under open-pit mining stage.

3. Stability monitoring design of northern anti-dip slope

Based on the influencing factors of deformation and failure, characteristics of the evolution stage and deformation trend of the anti-dip slope of the north slope, the monitoring and design of the anti-dip slope of the north slope of an open-pit mine after underground mining and open pit mining were conducted. The northern anti-dip slope is in the stage of rupture and evolution, and needs short-term monitoring.

3.1 Analysis of influencing factors and deformation trend of slope deformation and failure

The slope is in the stage of rupture and evolution, and the whole is tipping and slipping deformation. The influencing factors that need to be monitored are mainly rainfall and earthquake (vibration). The deformation failure factors and deformation failure parts are: ①Differential displacements appearing on the slope top surface area will gradually form ground fissures, and relative displacement monitoring is required. ②The slope surface has formed obvious differential displacement parts. The maximum differential displacement part of the slope surface is taken as the boundary of the key slope monitoring for absolute displacement monitoring. ③The shear stress concentration zone in the slope foot area needs to be monitored for stress and deep displacement.

3.2 Monitoring indicators

Relative displacement, absolute displacement, stress, vibration (seismic) motion, groundwater seepage pressure, groundwater level.

3.3 Monitoring location

According to the analysis of the deformation trend of the rupture evolution stage of the slope, the deformation monitoring parts are the differential displacement parts on the slope surface and slope top, the differential displacement parts in the deep part of the slope and the stress concentration area.

3.4 Monitoring method

The northern anti-dip slope uses the “instrument monitoring method” to monitor the slope displacement, stress and strain and environmental factors. The monitoring method is shown in Figure 14.

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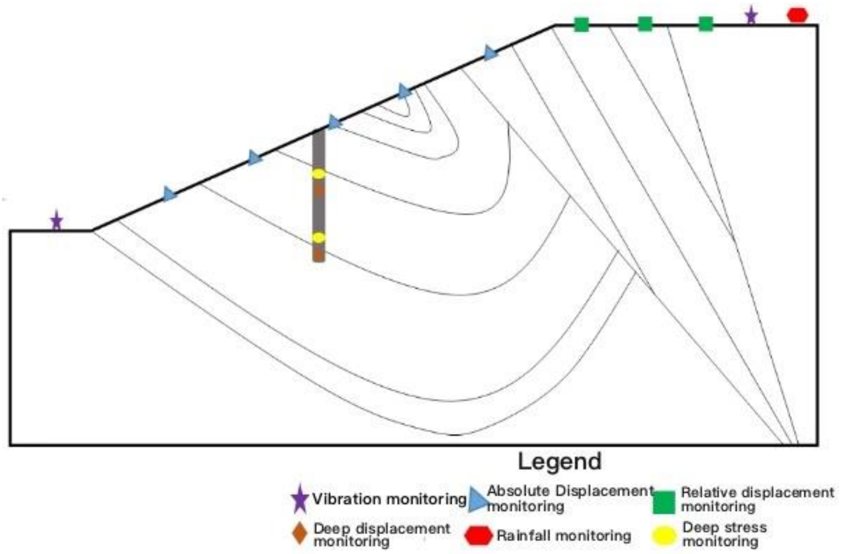

Fig.14 Schematic diagram of monitoring methods

3.5 Monitoring network layout

① Laying of deformation monitoring points on slope surface

The deformation of the slope surface is mainly obtained by laying absolute displacement monitoring points. First lay the "＋" survey line at the maximum displacement. Due to the large amount of subsidence in the upper part of the mined-out area and the amount of topping deformation in the upper part of the slope surface, a large number of instruments should be arranged and selected. Figure 15 is a schematic diagram of the placement of absolute displacement monitoring points on the slope table.

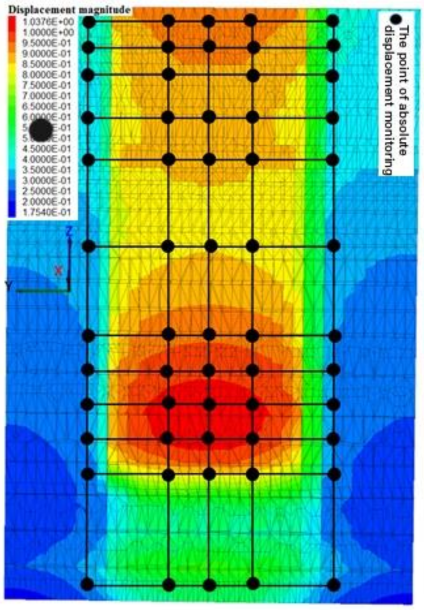

Fig.15 Schematic diagram of deformation monitoring points layout on slope surface

② Laying of deformation monitoring points on the top of slope

The deformation of the ground fissures on the top of the slope is mainly obtained by laying relative displacement monitoring points on the top of the slope. As shown in Figure 16, the monitoring points are arranged on the parts with different displacements at the top of the slope.

③ Arrangement of monitoring points for internal stress and displacement of the slope

Use boreholes to monitor stress and displacement at different depths inside the slope to observe the changes in stress and displacement of the slope shear stress concentration zone. The internal stress and displacement monitoring layout of the slope is shown in Figure 17 above.

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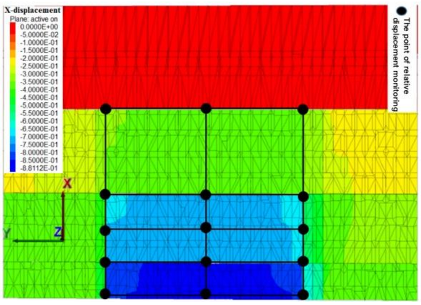

Fig.16 Schematic diagram of deformation monitoring points layout on the top of slope

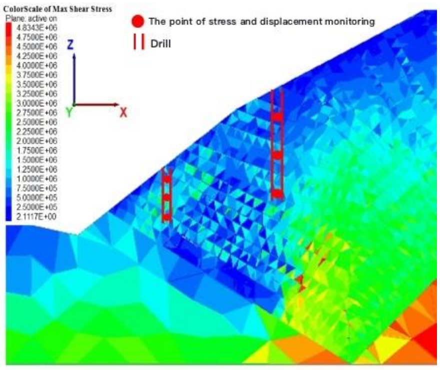

Fig.17 Schematic diagram of stress and displacement monitoring points layout on the interior of slope

4. Conclusion

(1) The anti-dip slope of the north side of the open pit is in the stage of rupture and evolution. The rock layer with a reverse dip structure and a large dip angle between the north flank of the syncline and the fault has been dumped and deformed when there is no mining activity. With the mining of underground coal seams, the slope of the north gang has formed the tipping slip deformation under the action of goaf subsidence and dumping force. After the underground mining is completed, the open-pit mining excavates the slope foot, which changes the vacancy condition and stress field of the slope, and the slope continues to fall and slide and deform.

(2) According to the characteristics of the above-mentioned slope deformation and failure evolution stage and deformation trend, the slope stability was monitored and designed.

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