Failure Mode for Creep Area of High Open-pit Slope Under the Influence of Underground Mining

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ABSTRACT: With mining intensity increasing, more and more deep open-pit mines are gradually transformed to underground mining in China nowadays. Focusing on a high open-pit slope under the influence of underground mining, the spatial distribution and development trend of slope displacement monitoring data were analyzed, combined with calculation of slope stability under different engineering conditions. The results show that the slope deformation has a periodic change with the seasons, and the rainy season is the most intense period of deformation development, when the tensile cracks on the third-level platform of the slope become penetrating channel for rainwater. The slope stability coefficient of the creep area under the unsaturated condition is 1.010 and the most dangerous sliding surface is located in the upper part, while potential sliding zones might be linked together and local slip might develop into overall failure in the role of heavy rainfall, and reasonably slope cutting can largely improve the slope stability. By studying the deformation process of the creep area, the deformation development characteristics and possible failure modes are got, and it could provide guidance to the reinforcement measures of landslides and ground subsidence.

KEYWORDS: Open-pit slope, Creep area, Underground mining, Stability analysis, Failure mode

1. INTRODUCTION

Practice shows that to identify the geomechanical mode for slope deformation and failure is the basis of the prevention and control of geological disasters (Huang, 2007). At present, theories and methods for the analysis and evaluation of slope stability can be generalized into two categories, which are qualitative comprehensive analysis of engineering geology and quantitative mathematical-mechanics calculation, mainly using the limit equilibrium methods and geotechnical numerical analysis methods for slope stability calculation and evaluation (Zheng, 2012; Tang, 2013; Chen, 2014).

Slope engineering is an open system with several pairs of problems needed to be researched, such as finite deformation and large deformation problems, immediate deformation and long-term deformation problems, at the same time, following with many natural science and social problems (Xu, 2009; Wang, 2011). There are a large number of large-scale open-pit mines in China (Yang, 2012), especially coal mines, and the average mining depth is increased with the continuous mining, and the economic costs increase at the same time. Therefore, more and more open-pit coal mines are gradually transformed to underground mining (Peng, 1989; Ji, 2012; Wu, 2013), and the development of slope deformation process has become more complex, which is influenced by the integrated effect of engineering geological conditions, rock and soil properties, periodic rainfall process, occasional earthquake, vegetation, reinforcement measures and other factors(Lin, 2009; Zeng, 2012; Camargo, 2016).

The deformation of open-pit slope is in a process of continuous development, with stress equilibrium state and slope stability state constantly changing. In rainy seasons, the mutual static and dynamic effect of rainwater is an important trigger factor of landslides that can not be ignored (Toyota, 2012; Jotisankasa, 2015), and it is necessary to study the deformation development characteristics of open-pit slope under combined influence of underground mining and other influencing factors, which has become an urgent technical problem to be solved at present.

In this paper, taking the engineering practice of high slope in the northwest pit of Antaibao coal mine as example, the deformation characteristics and slope stability under different conditions are researched based on monitoring data, and the deformation process and failure mode of open-pit slope under underground mining are studied. Respectively, the effect of underground mining on the deformation characteristics of open-pit slope is explored, and the stability characteristics of the slope under different combinations of engineering geological conditions is analyzed. Finally, the possible failure mode is described, which can provide reference for prevention and control of slope stability.

2. ENGINEERING BACKGROUND

2.1 Engineering geological conditions

Northwest pit of Antaibao open-pit mine is mainly covered by Quaternary system loess, as shown in Figure 1. The maximum height of the slope from bottom to the top is about 258m, and the pit includes several steps about per 30m from bottom to the top, with step width about 40m.

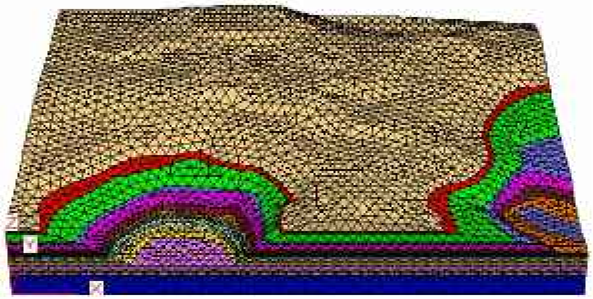
Figure 1 Full views of the open-pit mine

Slope area is in the east of Ningwu coal field, Shuozhou mining area of China, and in the north of Ningwu syncline. Loess is widely distributed in the well field, according to the exposed surface and revealed drilling, the stratum from old to new are Ordovician on ZhongTong majiagou group(O2s), the carboniferous ZhongTong existing group(C2b), the carboniferous taiyuan formation in stockings(C3t), Permian next tasseled shanxi group(P1s), the Permian stockings under stone box group(P1x), the Permian stockings on stone box group(P2s), Tertiary stockings on new(N2), Quaternary system(Q).

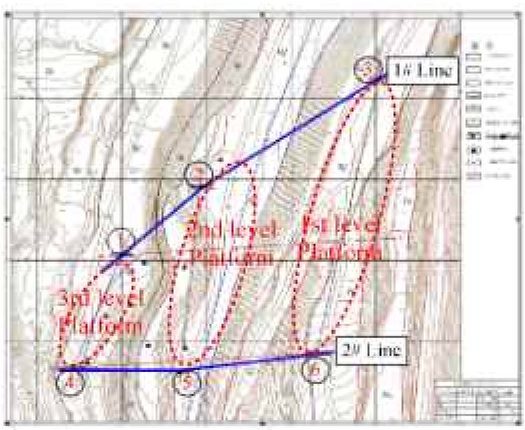
The high slope is located in mining area where the annual rainfall is 345.3~682.2mm, mostly concentrated in July, August and September. These three months accounted for 75% of annual rainfall, sometimes up to 90%, with maximum daily precipitation 87.0~153mm. The longest continuous precipitation time is 13 days.

Underground mining caused thick tensile cracks in the third-level platform, and the permeability increases with hydrogeological environment changed. With the continuous underground mining, the slope surface tensile cracks will gradually expand. In the rainy season, rainwater poured through surface cracks into the slope, and rainwater penetrating will further exacerbate deformation development and slope failure.

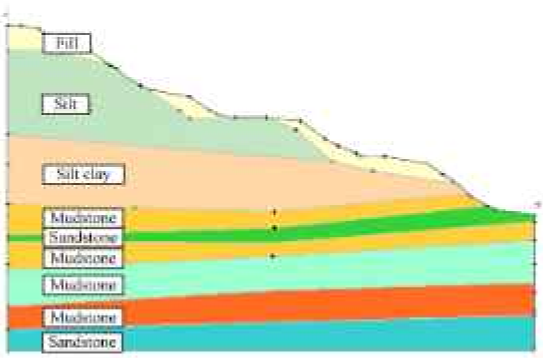
At present, there are a lot of penetrated cracks in the third-level platform, while only the lower part of the northwest pit has been protected by shotcreting, and drainage system has not been established in the upper slope. For the emphasized protection of creep area where a large-scale landslide happened, six boreholes along two survey lines were chosen to get the profiles and soil properties of creep area, as shown in Figure 2, and Table 1 shows the physico-mechanical parameters of 3 soil layers and 5 rock layers in the area.



(a) 3D model of the slope



(b) 2D topographic map of creep area



(c) Profile of 2# survey line

Figure 2 Sketch map of creep area

Table 1 Physico-mechanical parameters of media

No	Media	r/ kN • m⁻³	C/ kPa	Φ/(。)
1	Fill	19.9	5.0	27
2	Silt	20.0	28.8	24.6
3	Silty clay	20.0	44.7	21.3
4	Mudstone	23.3	2150	24.5
5	Sandstone	24.0	3230	28.6
6	Mudstone	23.8	3010	27.8
7	Mudstone	24.3	2240	25.6
8	Sandstone	24.1	1980	25.6

2.2 Underground mining condition

The coal mine includes three minable seams, and they are all Taiyuan formation coal seams, and now No.9 and No.11 coal seams are main minable seams.

Underground mining induces caving of overlying rock seams inner slope and tensile cracks on the slope surface, with slope rock mass integrity destroyed and the original rock strength decreasing. Slope stability is determined by slope deformation status, under the combined influence of underground mining and open-pit mining, leading to interacting mining effects, and it is a complex dynamic system. Layout of minable seams is shown in Figure 3.

Figure 3 Underground mining conditions

The mining work-face in NO.9 coal seam is much broader than gobs in NO.4 coal seam, but they are far away from the slope, mainly causing ground subsidence. As shown in Figure 3, there are five gobs in No.4 coal seam. Only gob 1 and gob 2 are linked together, causing obvious surface subsidence, while gob 4 and gob 5 are nearer to the slope surface, and play an important role in slope deformation and crack development. In this paper, only gob 5 of No.4 coal seam was concerned with the deformation and stability of creep area. At the same time, 3 typical sections of the slope are chosen for analysis, as shown in Figure 4.

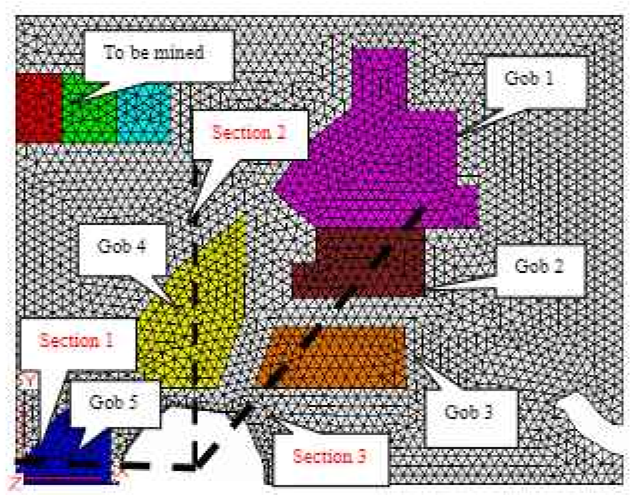
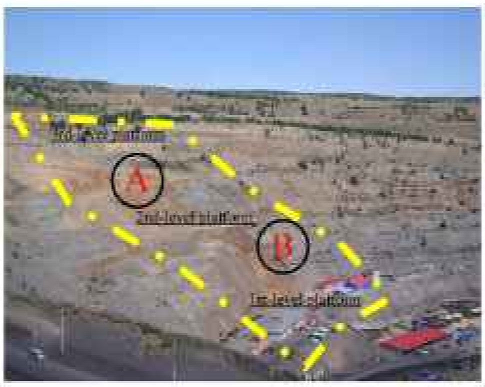


Figure 4 Layout of gobs in No.4 coal seam

2.3 Status of creep area

Creep area is located in the southwest of the slope, under the third-level platform, with a large number of tensile cracks on the upper third-level platform. Under the creep area lies Gob 5 of NO.4 coal seam, and natural exposure of upper soil leads to loosening of the surface soil and continuous deformation. At the beginning of this century, the creep area occurred an overall landslide with an earthwork of about 80,000 m^3, while soil instant slipped nearly 60m. Since then, the creep area has been closely monitored, especially the development of surface deformation, and the creep area is continuous moving, and a huge potential sliding body with length over 100 m has been formed, which is a potential threat.

Under the influence of open-pit excavation and underground mining, lots of cracks occurred on the third-level platform, about 100m from the bottom, which provided penetrating channel for surface water, especially the rainwater. At the same time, rainwater penetrating will promote the continuous development of cracks. Through investigation, it is found that the surface is covered with red clay in the area. Red clay is highly plastic clay, with high porosity and significant shrinkage, and it can easily become a gathering place of water. Therefore, this region is very likely to form a wedge sliding body, shown in Figure 5.



(a) Dangerous area

(b) Cracks on the third-level platform

(c) The third-level platform on the top of creep area

Figure 5 Creep area of northwest slope in Antaibao open-pit mine

At present, several wedge-shaped sliding bodies have been formed from the third-level platform, at the same time, the accumulation of rainwater and groundwater will erode the bedrock at the bottom of the slope, which will aggravate the failure of the slope. Roughly, there are potential sliding zone A and potential sliding zone B, and several monitoring points were located in the dangerous area.

3. DEFORMATION CHARACTERISTICS ANALYSIS

3.1 Two tendencies of slope deformation

Combining field investigation and engineering geology condition, software FLAC^{3D} is adopted to analyze the deformation process, and the calculation model of the high slope is generated according to geological survey, and then numerical simulation of deformation process is carried out.

In the numerical model, Mohr-Coulomb strength criterion is adopted to describe the failure criterion, and there are loess and other 14 rock layers, and Table 1 shows the physico-mechanical parameters of media used for creep area analysis, including 3 soil layers and 5 rock layers, which are determined by geological exploration.

Taking the three sections of the slope as example, as shown in Figure 4, positive horizontal displacement is defined as horizontal displacement away from the goaf side, and Figure 6 shows the horizontal displacement of each section with altitude changing, the extracted data at 170m and 130m of section 1 shows a displacement deformation towards goaf side, while other points towards outside. Section 2 and section 3 also produce a horizontal displacement to the goaf side at the two measuring points with high altitude, and other three monitoring points away from the goaf side. Although the points near the top of the slope produce a large retraction displacement towards goaf side, this deformation is beneficial for the overall stability of the slope, therefore, after extraction, the deformation of the overall slope is substantially stable. With the stopping face progressing of No.9 coal, the ground subsidence center will be transferred to the above of No.9 coal stopping faces, but slope deformation will not be obvious influenced because they are far away from the slope. Under the influence of coal stopping, the deformation response of high slope will enhance, vertical displacement will increase, and the development trend away from the goaf side will be more obvious.

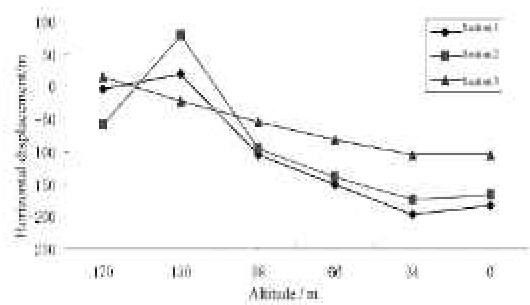
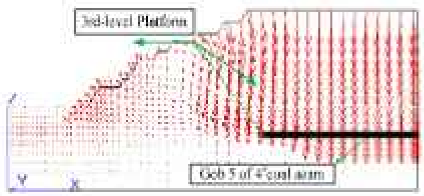
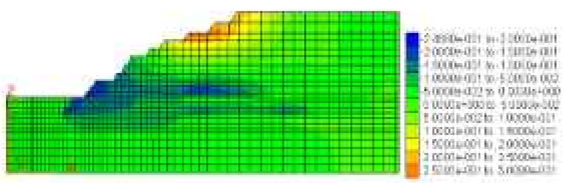


Figure 6 Horizontal displacement of monitoring points with altitude changes after underground mining

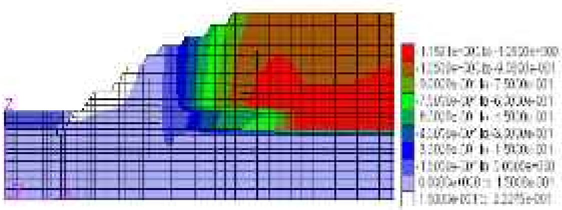
Figure 7 shows the deformation characteristics of section 1 after underground mining. The displacement vector changed obviously, and the slope has a tendency of deformation towards both apart and towards the gobs. On the top of the slope, the deformation is mainly vertical displacement towards underground mining gobs, while on the bottom the deformation is mainly horizontal displacement away from the gobs, resulting in shear stress concentration and widespread tensile plastic zones on the top of creep area, on the edge of the influence zone of underground mining. At the same time, a small number of shear failure zones appeared at the bottom of the slope. The opposite horizontal deformation direction of upper area and lower area leads to shear failure zones of the slope and ground subsidence. As a result, underground mining induces tensile cracks on the middle platforms of the high slope, almost the third-level platform in fact, with slope rock mass integrity destroyed and the original rock strength decreasing. After excavation, slope deformation is affected by complex underground mining and former open-pit mining, and latter underground mining will play a continuous impact on slope deformation development. Although mining activities do not occur near the creep area any more, slope deformation would go on changing.



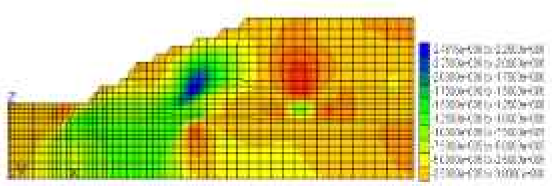
(a) Displacement vector



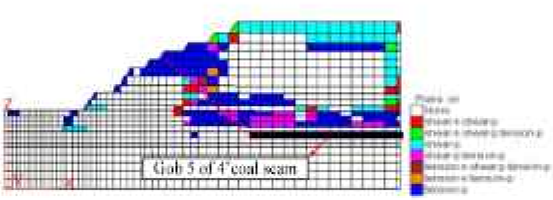
(b) Horizontal displacement (m)



(c) Vertical displacement (m)



(d) Shear stress (Pa)



(e) Plastic zones

Figure 7 Deformation characteristics after underground mining

3.2 Spatial distribution of slope displacement

In order to monitor the deformation development of slope, 93 displacement monitoring points were arranged in the middle and lower parts of the northwest slope and the east dump, 85 monitoring points on the northwest slope and another 8 monitoring points arranged in the east dump, and displacement data of each monitoring point was collected every 10 days. For the convenience of spatial displacement interpolation, the maximum cumulative displacement of each monitoring point during the rainy season was taken as the initial data, while 11 other points at the bottom of the pit were selected as the zero points with displacement values assumed to be zero. A total of 104 discrete data were acquired in the whole monitoring square area, and then the database was built and imported into ArcGIS software to build surface TIN model. The displacements are the overall displacement of each monitoring point. It could be considered as Eq. (1).

$$s = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \tag{1}$$

where x,y,z are the monitored coordinate values by GPS total-station.

Using the Kriging interpolation method (Kriging), which is suitable for spatially interpolating of related spatial data, the displacement were interpolated and the spatial distribution of displacement in the monitoring area was obtained based on the spatial analysis module of GIS. The displacement attribute values of grids were roughly classified into different classes from small to large, and the interpolation result were displayed in ArcScene, as shown in Figure 8, while the grid size was 1m×1m.

It can be seen from Figure 8 that the classification value of the upper part of the slope and the creep area are larger, and with the increase of slope and elevation, the displacement will increase correspondingly.

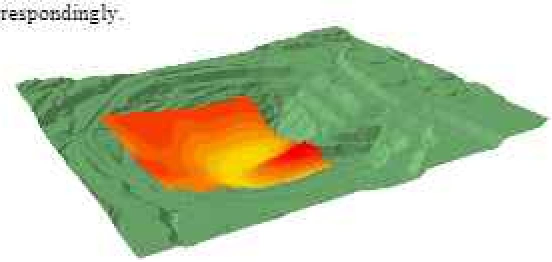


Figure 8 Spatial distribution of displacement reclassification value

Statistical sensitivity analysis of different factors was done. The thickness of covered soil was analyzed from 6 drilling boreholes in creep area, ranging from 0 to 50.5m, as Table 2 shows. With the increase of the altitude, the thickness of covering soil basically increased, and the correspondence between higher displacement classification value and the thicker covering soil layer is obvious in the creep area. The total earthwork in the creep area is about 488475m^3 after interpolation of soil thickness and grid calculation, and thicker covering soil layer is a risky factor for slope deformation and landslide occurrence, especially for potential sliding zone A.

Table 2 Soil thickness of six drilling boreholes

No.	1	2	3	4	5	6
Soil Thickness/m	32.5	50.5	26.2	9.5	0	6.7

3.3 Displacement data analysis

Displacement trend of four displacement monitoring points with time is shown in Figure 9. NO.1 point and NO.2 point were located on the second-level platform of the creep area, and NO.3 point and NO.4 point were located on the upper third-level platform of the creep area. As can be seen, the displacement development of the slope is substantially stable at present, but in the rainy season, slope surface deformation increased accordingly, and at the end of the rainy season displacement value would fall.

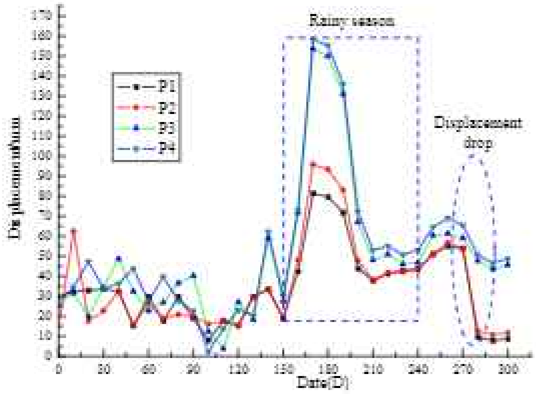


Figure 9 Displacement trend of 4 monitoring points

Displacement response during rainy season indicated that the rainwater penetrating would promote the development of slope displacement periodically, and the rainy season was the most intense period of deformation development. Though the lower part of the northwest slope had been reinforced by shotcreting, which lowered the influence of rainwater, and in other cases, the slope is not stable under the effect of combined factors, and an abnormal amount of rainfall during rainy season could be a great risk to slope stability, when creep deformation would be fully developed. Therefore, we must closely monitor in the area and take necessary reinforcement measures.

The east dump is merely influenced by underground mining, and it is composed by single fill soil. For comparison, displacement trend of two displacement monitoring points located on the east fill dump is shown in Figure 10. NO.5 point was located in the upper part of east dump, and NO.6 point was located in the upper part of east dump. As can be seen from Figure 10, the displacements increased continuously in the rainy season, about 50 mm per month, corresponding with the rainy season in the region. After the rainy season, the monitoring displacement continued to increase, but the growth rate was obviously reduced. At the same time, the deformation response of dump slope to the rainfall was obviously real-time compared with the open-pit slope formed by open excavation.

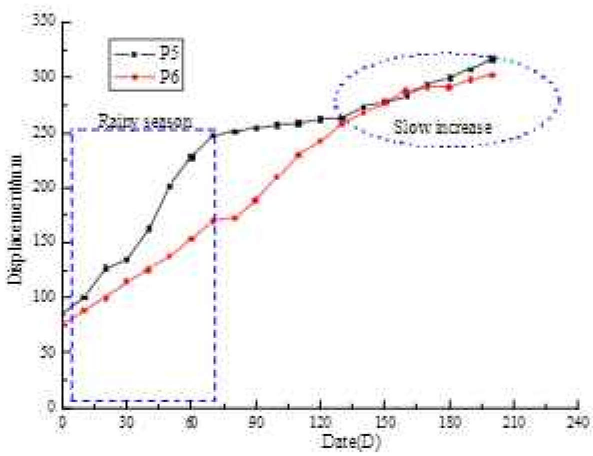


Figure 10 Displacement trend of 2 monitoring points

It is worth noting that the resilience of displacement is an evidence of the failure possibility, showing that the creep area is linked as a whole with overall failure risks. Under the influence of rainy water or earthquakes, slope deformation would be obviously developed, however, when the deformation is not sufficient for a sudden landslide, there will be a resilience or spring-back of the whole sliding mass.

4. FAILURE MODE ANALYSIS

4.1 Slope stability analysis

According to the slope deformation characteristics and landslide hazard in creep area, slope stability calculation and dangerous sliding surface analysis were carried out based on limit equilibrium method (Janbu, 1973). The stability of creep area was analyzed under the following three representative conditions, as Table 3 shows.

(1) Slope stability analysis under unsaturated condition.
(2) Slope stability analysis under water-saturated condition.
(3) Slope stability analysis under slope cutting condition.

Table 3 Safety factor under 3 conditions

Condition	unsaturated	Saturated	Slope cutting
Fs	1.010	0.841	2.808
Dangerous area	A	A+B	B

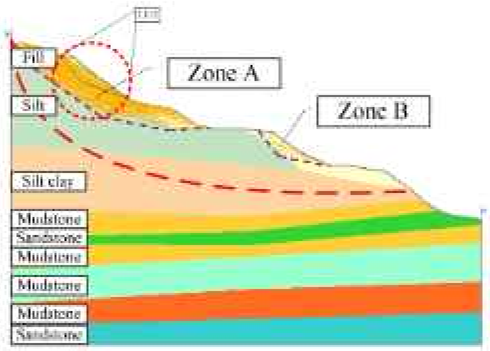
Combined with the SLIDE software, slope was divided into 50 strip blocks, then the slope stability under the 3 conditions after was simulated and analyzed using the path search method, while the water-saturated condition was simplified by setting saturation lines on the slope surface. The influence of rainfall water was presented by setting different saturation lines in SLIDE software, as the blue line in Figure 11(b) shows, and the drainage condition was assumed to be unsaturated, without saturation line during analyses.

The results show that the safety factor under saturated water condition is about 0.841 and the most dangerous sliding surface is located in the upper slope, passing through the upper soil and silty soil, including potential sliding zone A and potential sliding zone B. While the slope stability coefficient under the unsaturated condition is 1.010, and the slope is basically in limit equilibrium state, and the most dangerous sliding surface is still located in the upper slope, only part of potential sliding zone A, whereas sliding zone is obviously reduced compared to saturated condition and sliding surface is also decreased. Figure 11 shows dangerous zones under unsaturated condition, the green line represents the most dangerous sliding surface, while the yellow lines show sliding surfaces with Fs less than 1.30. Under water-saturated condition, the most dangerous sliding surface are represented by the red line, with a tendency of potential sliding zone A and B connected together.

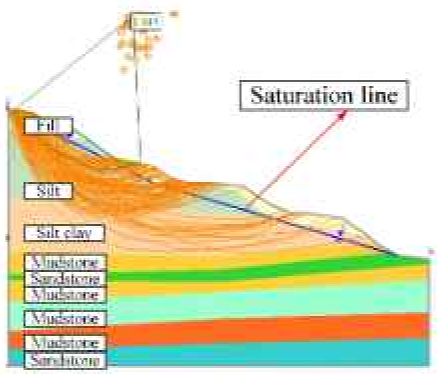
Under the water-saturated condition, the dangerous sliding surface increases obviously, and the potential sliding zone A and potential sliding zone B are connected, namely that the Fs of whole failure is less than 1, and local slip may develop into overall failure in the role of heavy rainfall.

Under the assumed slope cutting condition, the Fs of sliding surfaces increases obviously and the most dangerous sliding surface is transferred to zone B. The Fs is about 2.808, and the stability of both local zones and overall area are obvious enhanced .

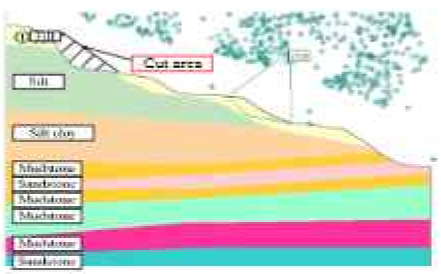
For important projects in China, Fs should be more than 1.30, and by reasonable slope cutting of potential sliding zone A, the stability of both potential sliding zone A and whole creep area could be improved.



(a) Potential sliding zones



(b) Water-saturated condition



(c) After slope cutting of potential sliding zone A

Figure 11 Sliding surfaces under different conditions

4.2 Failure mode for creep area

After open-pit excavation, the slope body has a tendency of deformation towards airside, while the subsequent underground mining caused mainly vertical subsidence deformation towards underground mining gobs. Under the combined action of the two deformation trends, there are two possible failure modes.

(1) local slip

The covering soil of the creep area is affected by the historical landslide and long-term weathering, and local slip can be seen as a dynamic adjustment process of the whole slope system, while the region not reinforced is basically in the limit equilibrium state. In the creep area, creep slip often first produces small local slip surfaces in different parts of the slope, which is closely related with slope gradients and soil thickness in different parts of the creep area. There are potential sliding zone A and potential sliding zone B in the limit equilibrium state when the influence of rainwater penetrating is neglected. At present, the two dangerous zones are not connected under the drainage condition.

At the same time, under the combined effect of open-pit mining and underground mining, a large number of tensile cracks formed in the third-level platform, and the rainfall is converted into groundwater, and soaking and penetrating effect of rainwater continuously weaken the physical and mechanical properties of rock and soil, increasing sliding force at the same time. The deformation and tensile cracks of slope body will be further expanded in the future, and the local slip risk will further aggravate under the condition of periodic heavy rainfall or occasional earthquake.

Deformation of the slope body or even local slip is allowed, and different areas have different requirements on the control of slope deformation and reasonable selection of deformation control measures is necessary. According to the results of stability analysis, it is necessary to carry out slope cutting of potential sliding area A to prevent local slip, while decreasing the sliding force of potential sliding area B and increasing the overall stability of the slope at the same time. In addition, an effective slope surface drainage system should be established to prevent the infiltration of rainwater from deteriorating the internal environment of the slope, combined with anchor and shotcreting protection of vulnerable parts, with cracks and gully filling compact backfilled. Reasonable drainage system and measures to prevent rainwater are the basis of the comprehensive prevention and treatment of local slip, and other measures such as cutting slopes, prestressed anchor cables or strengthening piles should be taken.

(2) Overall failure

Creep deformation tends to occur series of small local slip surfaces first, and then partial slip surface gradually linked into a continuous sliding surface, resulting in a slow slide. Under certain conditions, it may produce a wholesale slide along the sliding surface.

The internal sliding surface of the creep area has been connected with the bottom after historical landslides, and the creep area is in another landslide cycle based on the old slip surface, and the evolving creep deformation may cause the occurrence of landslide again under the action of external factors.

The two kinds of opposite horizontal deformation tendencies induce tensile cracks on the third-level platform of the slope, which became penetrating channel of rainwater, and an abnormal amount of rainfall during rainy season can be a great risk for slope stability. In the creep area, there is a red clay layer in the overlying soil, and the permeability of the clay is low, while the relatively gentle inclination of the bedrock layers creates the catchment surface, and along with the shear stress concentration in slope foot, the whole landslide of the creep area is prone to happen.

Tensile cracks in the third-level platform of the slope caused by underground mining, historical landslides and rainwater infiltration constitute the three elements of the overall slope failure, and determine the formation of the ever-expanding slip surface and landslide cycle, and the shear stress concentration in slope foot along the horizontal bedrock layer create the condition for creep-tension-shearing mode of a landslide. With the soaking and penetrating effect of rainwater continuously weakening the physical and mechanical properties of rock and soil, the anti-sliding force of the potential wedge-shaped sliding body is reduced and the sliding force is increased considering water wedge effect under certain rainfall conditions. The potential wedge would exert an increasing downward thrust on the front body and keep developing. The expanding sliding surface and the decreasing soil and rock properties decrease the anti-sliding force of the slope, and the overall failure is likely to happen again under the influence of the increasing rainfall or the continuous deformation development. The overall failure mode of the creep area is shown in Figure 12, while the displacement angle represents the range influenced by underground mining.

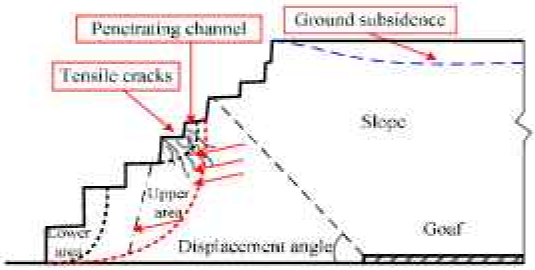


Figure 12 Overall failure mode of creep area

5. CONCLUSION

Based on the deformation development process and possible failure modes of the creep area located at a high open-pit slope, the following conclusions are obtained.

1) Tensile cracks occurred on the third-level platform of the slope upper the creep area under the influence of underground mining. Slope deformation had a periodic change with the seasons, and the rainy season was the most intense period of deformation development, when the tensile cracks on the top of the slope became penetrating channel of rainwater, and an abnormal amount of rainfall during rainy season can be a great risk for slope stability.
2) The total earthwork in the creep area is about 488475m^3, and thicker covering soil layer is a risky factor for slope deformation and landslide occurrence. The Fs under the unsaturated condition is 1.010 and there are two potential sliding zones A and B for the creep area, while the most dangerous sliding surface is potential sliding zones A, and the slope is basically in limit equilibrium state. Fs under saturated water condition is about 0.841 with most dangerous sliding surface connecting potential sliding zone A and potential sliding zone B, and local slip may develop into overall failure in the role of heavy rainfall .
3) Under the combined action of the two deformation trends, there are two possible failure modes for the creep area. Tensile cracks in the third-level platform of the slope caused by underground mining, historical landslides and rainwater infiltration constitute the three elements of the overall slope failure, and determine the formation of the ever-expanding slip surface and landslide cycle. The deformation and tensile cracks of slope body will be further expanded in the future, and the local slip risk would further aggravate under the condition of periodic heavy rainfall or occasional earthquakes. Effective drainage system and measures to prevent rainwater are the basis of the comprehensive prevention and treatment of landslides, while reasonable slope cutting of potential sliding zone A is essential for the prevention of both local slip and overall failure.

Deformation monitoring of the creeping area should be strengthened in the following landslides prevention practice, while local slip and overall failure should be unified when taking control measures.

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