Research Article

Steep End-Slope Mining and Slope Stability of Extremely Thick Inclined Coal Seam Open-Pit Mine

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Considering the characteristics of extremely thick inclined open-pit coal mine with large amount under end slope, large end-slope height, and long exposure time, it is important to study the slope stability research during open-pit mining. This study takes the whole process of excavation descending and steep end-slope mining of an extremely thick inclined open-pit mine as the background. The slope stability factor of the end slopes were calculated for each stage of mining with different coal seam thicknesses by using the strength reduction method. The slope data, such as vertical stress, horizontal stress, and increment of maximum shear strain, are analyzed. The results show that the vertical stress and stability factor are decreasing throughout the mining stage. The horizontal stress shows a pattern of increasing and then decreasing in the excavation descending and steep end-slope mining. The greater the thickness of coal seam, the less the stability of the slope.

1. Introduction

Open-pit mining is an important method of mining coal resources because of its large scale of production and safe operating conditions [1]. Xinjiang is an important coal resource mining area in China [2, 3]. Most of the coal seams are characterized by large thickness, simple distribution, and inclined or gently inclined coal seams. The overlying coal resources in the open-pit mine of extremely thick coal seam are generally recovered by means of steep end-slope mining. In addition, infill mining techniques [4, 5], which are widely used in shaft mines, can also be applied to improve the stability of the slopes of opencast mines and further recover coal resources. The increase in coal seam thickness leads to a relative reduction in overburden and slow follow-up of the inner dump. Therefore, the exposure time of the open-pit end slope is prolonged and the exposure area is significantly increased [6, 7]. This situation is not conducive to the slope stability of the end slope nor to the further recovery of coal resources under the overburden of the end slope by steep end-slope mining [8].

Meanwhile, the overburden thickness increases with the mining of inclined coal seam open-pit mine [9]. The load on the upper part of the end slope increases, and the extremely thick coal seam has been in the lower part of the slope as a soft layer, which is extremely unfavorable to the stability of the slope. Therefore, it is of great significance to analyze the stress distribution, stability factor changes, and slide types of slopes during mining of open-pit mines with extremely thick inclined coal seams to ensure energy supply and personnel safety in the area [10, 11].

The methods for slope stability calculation mainly include the limit equilibrium method [12], the finite element method based on the principle of continuous medium mechanics [13], the finite difference method [14, 15], and the discrete element method [16]. In the study of slope stability in open-pit mines, Guo et al. [17] proposed different land-saving and loss-reducing surface mining schemes and inner
dumping measures by changing the geometry of the end slope of extremely thick coal seam open-pit mine, with good results in field application. Tao et al. [18] analyzed the rock stress state, slope stability, and inter-structure relationship during the formation of end slope by the finite difference method to determine the change law of slope stability factor with inner dump parameters. Yin and Dong [19] analyzed the relationship between seepage pattern, number of excavated seams, coal pillar parameters, and slope stability when the end slope of extremely thick coal seam was mined by SHM end-slope coal miner through numerical simulation. Bar et al. [20] obtained the sliding surface and stability factor of slopes by the three-dimensional limit equilibrium method to provide ideas for optimizing the conservative design of slopes. Bo [21] analyzed the sliding modes and stability factor of composite slopes of open-pit mine with extremely thick coal seams in Xinjiang and gave the safe distance between the dump and slope in open-pit production. Peng et al. [22] analyzed the progressive damage process and slope damage types in the excavation process of open-pit mine slopes. Behbahani et al. [23] analyzed the multistage clearing operation of open-pit mine slides and gave the deformation characteristics of slides in different clearing stages. Inclined coal seams in surface mining will constitute high and steep downward slopes, which are highly susceptible to large deformations or slides caused by environmental influences. Li et al. [24] analyzed the damage mechanism and stress distribution of the end slope of the inclined coal seam in Xinjiang and obtained that the deformation of slope with inclined base is mainly in horizontal direction, and the maximum horizontal displacement is concentrated in the area of the toe of the slope. Cao et al. [1] analyzed the stability of the top slope of an inclined coal seam open-pit mine under different slope angles and improved the resource recovery rate by determining the potential sliding mode of the slope through the limit equilibrium method and finite difference method. With the development of computers and other technologies, machine learning and other techniques are being used in mining [25, 26]. Many scholars used big data analysis to determine the stability of slopes [27].

Few existing studies have analyzed the slopes of open-pit mines with both extremely thick and inclined coal seam. In this paper, the stress distribution, stability factor change, and slip surface morphology change during the mining of extremely thick inclined coal seam will be investigated for this problem. It also proposes the steep end-slope mining scheme and analyzes the effect law of slope angle on stability factors.

2. Materials and Methods

2.1. Characteristics of Open-Pit Mining. Extremely thick inclined coal seam generally exceeds 30 m (locally even over 200 m), and the dip angle of the strata exceeds 10°. In this kind of coal seam in the process of surface mining, the pit depth will increase year by year with the advancement of the working slope, and the production stripping ratio increases (Figure 1) [28]. If the mining and transportation equipment remain unchanged, the annual production capacity of the mine will be reduced by the limitation of equipment capacity as the coal floor moves downward and the material stripped above the coal seam increases. There will be no major changes in the purchased equipment for 3–5 years, and the mine will have a constant amount of stripping per year (S1 = S2). The advancing distance of the working slope will gradually become smaller with the descending depth of the pit bottom each year (a1>a2), and the coal mining volume will be reduced year by year. However, when stripping is done by an outsourced company, the equipment for extraction and transportation can be easily adjusted. This allows the mine to extract the same amount of coal each year, the same advance each year (a1 = a2), with an increase in stripping (S1<S2).

Due to the burial characteristics of the extremely thick inclined coal seam, the exposed area of the end slope during mining will be different from that of the near-horizontal coal seam open pit (Figure 2). As mining proceeds, the vertical depth (H1) at the toe of working slope and the vertical depth (H2) at the toe of the inner dump increase, and the exposed length (L) at a certain level on the end slope increases. By adjusting the equation proposed by Cai et al. [6], the exposed area of the end slope of the open-pit mine with extremely thick inclined coal seam is observed to further increase. This puts the slope stability under serious threat. Where H is the vertical depth of a position on the end slope, m; H1 is the vertical depth of the working slope, m; H2 is the vertical depth of the inner dump; φ is the slope angle of the working slope, °; θ is the slope angle of the inner dump, °; γ is the dip angle of the coal seam, °; L is the exposed length of a level on the end slope, m; and D is the safe distance between the inner dump and the working slope, m.

\[
\begin{align*}
L &= L_1 + L_2 + L_3, \\
L_1 &= \frac{H_1 - H}{\tan \phi}, \\
L_2 &= \frac{D}{\cos \gamma}, \\
L_3 &= \frac{H_2 - H}{\tan \theta},
\end{align*}
\]

2.2. Numerical Modelling. Firstly, Figure 3 shows the end-slope morphology at different stages of open-pit mining with extremely thick inclined coal seams. In Figure 3(a), L1 and N1 are the location of the working slope and the location of the inner dump before advancement, and L2 and N2 represent the location after advancement, respectively. As shown in Figures 3(b)–3(d), the thickness of the overburden increases with the advance of the working slope, and the coal seam is always located at the bottom of the end slope.

Numerical simulations reflect the characteristics of end slopes during open-pit mining of extremely thick inclined coal seams. In numerical calculation models with different thicknesses of coal seams, the position of coal seam bottom remains unchanged.
The mining procedure of the analyzed open pit is full area longitudinal mining with coal seam dip angle of $7^\circ$. The end-slope profiles of the working slope advancing to 0 m, 1000 m, 2000 m, 3000 m, and 4000 m were selected for analysis. The slope angle of the end-slope sides on both sides is $36^\circ$, and steep end-slope mining starts when the bottom of the pit is descended to the lowest depth. Figure 4 shows the simulation model when the coal seam thickness is 50 m.
3. Results

In extremely thick inclined open-pit mining, as the working slope advances, the pit bottom level decreases. Steep end-slope mining operations begin when the pit bottom is at the lowest level. During this period, the vertical stress of the end-slope is always distributed continuously on the surface and the bottom of the slope in a concave surface, and in the bottom of the pit in a horizontal laminar distribution, the vertical stress decreases with the mining process. The maximum horizontal stress is concentrated inside the end slope, which increases as the excavation descends and decreases as the steep end-slope mining proceeds. The slope stability factor of the end slope shows a decreasing trend in both the excavation descending and steep end-slope mining.

3.1. Mining and Bottom Descending. Figure 5 shows the vertical stress variation law at different stages of working slope advance when the coal seam thickness is 150 m. As mining proceeds, the original rock stress is destroyed and the unbalanced stress is unloaded along the slope and pit bottom in the direction of the critical surface. The unbalanced stress extends deeper into the open pit. Meanwhile, the vertical stress during excavation is always continuously distributed along the ground surface and slope bottom in concave curved layers. The horizontal laminar stress state is restored at the bottom of the pit. It is worth noting that the stress distribution is similar for coal seam thicknesses of 50 m, 100 m, and 150 m, so only the stress distribution at 150 m is described. As shown in the figure, the stress unit is Pa.

Figure 6 shows the horizontal stress variation law at different stages of working slope advance when the coal seam thickness is 150 m. As the working slope advanced, the shallow rock structure is destroyed and the horizontal stress is out of balance. The horizontal stress in the upper out-of-balance rock is bent downward, the horizontal stress at the slope face of the side slope is increasing, and the stress concentration phenomenon of the horizontal stress taking the center line of the stope as the axis appears in the intact rock below the stope. The elastic-plastic deformation of slope toe rock mass is caused by long-term stress on both sides of the stope, and the bottom of the stope shows a trend of uplift, which has a negative impact on the stability of the slope, and the end slope on both sides shows a trend of sliding towards the stope.

Figure 7 shows the stability factor of end slope during the mining process of different thickness coal seam models. As the mining process proceeds, the height of the end slope on both sides increases, and the stability factor of the slope gradually decreases as a negative exponential function and converges to the limit equilibrium state. In addition, because of the certain difference in coal seam thickness, when the height of the slope is bigger, the difference causes the influence to decrease and the difference in stability factor decreases. At the early stage of open-pit excavation, the initial ground stress is destroyed and the slope stability factor decreases faster, but the amount of stability factor is larger and the risk of landslide is smaller.

3.2. Steep End-Slope Mining. When the mine excavation descends to the end of the section, the bottom of the pit is descended to the lowest level and then the steep end-slope mining operation begins, and the angle of the end slope becomes larger continuously. The change pattern of vertical stress on the end slope is not much different from the previous, and the horizontal stress decreases.

Figure 8 shows the horizontal stress variation law of the end slope during the steep end-slope mining of 150 m coal seam thickness model. The horizontal stress in all stages of steep end-slope mining appears as stress concentrations on the axis of the midline of the stope. The horizontal stress tends to decrease as the angle of the end slope keeps getting larger. As shown in Figure 8(a), the internal horizontal stress of the end slope has a light green distribution, and the size is in the range of 2.50–4.00 MPa. But in Figure 8(d), the internal horizontal stress of the end slope gradually becomes yellowish distribution with the size of 1.75–2.50 MPa.

Figure 9 shows the variation law of the maximum shear strain increment of the end slope with the 150 m coal seam thickness model. At the early stage of mining (Figure 9(a)), the maximum shear strain increment is distributed in a
Figure 5: Vertical stress variation of end slope during mining (coal seam thickness is 150 m).

Figure 6: Horizontal stress variation of end slope during mining (coal seam thickness is 150 m).

Figure 7: End-slope stability factor of coal seam models with different thicknesses.
circular shape inside the rock body of the end slope, which is due to the small horizontal stress inside the end slope at the early stage of mining, and there is no obvious stress concentration area inside the slope. As mining proceeds, the slope increases with the internal horizontal stress of the excavated descending section, and the maximum shear strain increment is concentrated in the lowermost part of the end slope and sheared out along the junction of the slope and bedrock, with obvious stress concentration phenomenon. When the excavation descending section is completed (Figure 9(d)), the mine conducts steep end-slope mining operations. In Figure 9(f), the slope angle increases from 36° to 38°, and the distribution of the maximum shear strain increment spreads from concentrated along the junction of the slope and bedrock to the whole rock interior of the slope. This is due to the decreasing law distribution of horizontal stress inside the end slope as the steep end-slope mining proceeds, and the phenomenon is more obvious when the steep end-slope mining reaches 42°, and the stress concentration phenomenon almost disappears.

Figure 10 shows the stability factor of different stages of steep end-slope mining with different coal seam thickness models. With the progress of steep end-slope mining, the coal resources under the overlying end slope are extracted, the slope angle becomes larger continuously, the slope stability factor decreases as a quadratic function, and the decline increases with the progress of steep end-slope mining. Comparing the same slope angle with different coal seam thickness, the slope stability factor is smaller because the thicker the coal seam is, the higher the slope height is, and the mechanical properties of the coal seam are weaker.

4. Discussion

4.1. Stress Variation. The vertical stress is the self-weight of the rock mass. The self-weight of the rock mass and Poisson effect cause the horizontal stress [29], whose magnitude can be calculated according to the following equation:

\[ F = \frac{\mu}{1-\mu} \gamma H, \]

where \( F \) is the vertical stress, kN, \( \gamma \) is the weight of the overlying rock mass, kN/m, \( \mu \) is Poisson’s ratio, and \( H \) is the height of the overlying rock mass, m.

Equation (3) shows that when the slope is homogeneous, the rock mass density and Poisson’s ratio are constant (can be regarded as constant); then, the vertical stress is linearly related to the height of the overlying rock mass. In this simulation, the slope is composed of overlying rock, coal seam, and bedrock, and it is a non-homogeneous slope, and the rock mass density and Poisson’s ratio are not the same, so only the vertical stress can be determined to be positively related to the mining depth.

With the increasing mining depth, the vertical stress of the lower rock body of the slope increases continuously and the Poisson effect is more obvious, which is consistent with the simulation results in Figure 5 that the vertical stress increases with the increasing mining depth.

As the height of the end slope increases, the effective impedance length at the bottom of its slope also grows linearly, and the effective shear strength provided by the rock at the bottom of the end slope can be calculated according to the following equation:

\[ \tau = \sigma \tan \varphi + C L_r = \sigma \tan \phi + C \frac{H}{\tan \alpha}, \]

where \( \sigma \) is the normal stress on the upper part of the slope, kN; \( \varphi \) is the angle of internal friction of the rock mass, °; \( C \) is the cohesive force of the end-slope rock, kPa; \( L_r \) is the effective impedance length at the bottom of the end slope, m; \( H \) is the height of the end slope, m; and \( \alpha \) is the angle of end slope, °.

In equation (4), the normal stress on the upper part of the slope is provided by the gravity of the overlying rock, the magnitude of which can be calculated according to the following equation:

\[ \sigma = \frac{\gamma H^2}{2 \tan \alpha}, \]

Substitute (5) into (4) to obtain the effective shear strength of the slope.
\[
\tau = \frac{\gamma H^2}{2 \tan \alpha} \tan \phi + C \cdot \frac{H}{\tan \alpha}
\]  

(6)

The effective shear strength of the slope is equal to the sum of the vertical stress and the horizontal stress, and the horizontal stress is obtained as

\[
F_h = \frac{\gamma H^2}{2 \tan \alpha} \tan \phi + C \cdot \frac{H}{\tan \alpha} - \mu \frac{\gamma H}{1 - \mu}
\]  

(7)

From equation (7), it can be seen that the horizontal stress is a quadratic function about the height of the end slope, which is consistent with the functional relationship obtained from the numerical simulation analysis. In Figure 6, with the continuous excavation descending section, the height of the end slope increases continuously. The horizontal stress shows an increasing trend.

At the same time, when the angle of end slope keeps getting larger, the horizontal stress decreases, which is also consistent with the fact that the horizontal stress decreases with the increase of the end-slope angle in Figure 8.

4.2. Stability Factors and Benefits. In Figure 10, the slope stability of different coal seam thickness models is negatively correlated with the end-slope angle. As mining proceeds, the relationship between the rate of decline in stability and the amount of coal mined from the steep end-slope mining changes. Figure 11 shows the variation relationship between the amount of coal extracted and
stability in the model of steep end-slope mining for different thicknesses of coal seams, and the amount of coal extracted by steep end-slope mining is expressed by using the coal mining area in the side slope profile (only unit thickness is considered). The greater the thickness of the coal seam, the lower the stability of the end slope, but the stability factor decreases with the increase of the coal seam thickness. In the early stage of steep end-slope mining, the larger the thickness of coal seam under the same slope stability factor, the smaller the amount of coal mined from the steep end slope. When the coal extraction volume exceeds 8150 m$^3$, the larger the coal seam thickness under the same slope stability factor, the larger the coal extraction volume of the steep end slope. For example, when the safety and stability factor is 1.2, the coal extraction volume of the steep end-slope mining with coal seam thickness of 50 m, 100 m, and 150 m is 13710 m$^3$, 25817 m$^3$, and 31350 m$^3$, respectively.

5. Conclusions

In the process of mining, as the working slope advances, the production stripping ratio becomes larger and an amount of coal resources is pressed under the end slope. The height of end slope on both sides has been increasing, and the extremely thick coal seam has been in the lower part of the slope as a soft layer, which is extremely unfavorable to the stability. In order to recover the coal resources under the end slope, steep end-slope mining is required, so the stability of the slope is further reduced. By study on the open-pit mine where the extremely thick inclined coal seam is endowed, the stress changes, stability factors, and slip surface types of end slope during the excavation descending and steep end-slope mining process were analyzed.

The results show the following:

(1) As mining progresses, the mining depth increases and the height and exposed area of the end slopes on both sides of extremely thick inclined open-pit coal mine increase. The stripping volume and coal mining volume of the mine under the no outsourcing mining model will decrease yearly.

(2) The vertical stress of the end wall always presents a continuous concave surface layered distribution along the ground surface and slope bottom, and a horizontal distribution at the bottom of the pit. The vertical stress tends to decrease with the development of the excavation descending and steep end-slope mining. The horizontal stress distribution shows a stress concentration phenomenon with the center line of the slope as the axis, which tends to increase in excavation and decreases in the steep end-slope mining.

(3) The maximum shear strain increment of the end slope is uniformly distributed in a circular shape at the early stage of mining and concentrated on the lowest part of the end slope as the excavation proceeds, and an obvious stress concentration phenomenon appears. With the end of the excavation descending and steep end-slope mining, the distribution of the maximum shear strain increment spreads from concentrated along the junction of the slope and bedrock to the interior of the whole slope.

(4) The stability factor of the end slope decreases with the excavation descending and steep end-slope mining, respectively, as a negative exponential function and a quadratic decreasing function. The stability decreases with the increase of coal seam thickness, but with the increase of end-slope height, the slope stability gradually decreases due to the difference of coal seam thickness.

(5) Through theoretical analysis, the vertical stress and Poisson effect of the slope are observed to increase.
with the increase of mining depth. The horizontal stress is a quadratic function of the height of the end slope. The horizontal stress decreases as the end-slope angle becomes larger and larger.

Data Availability

The raw/processed data required to reproduce these findings cannot be shared at this time as the data also form part of an ongoing study.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References


