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ORIGINAL PAPER

The Coal Mining Model Under Slippery Slope in Yiminhe Open Pit Coal Mines

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Abstract To study the unloading of in situ rock stress in coalmining process, mechanics analysis has been carried out, according to which, a stress unloading arch tends to come into being where the slopes are of short strike length. Due to the differences existing between the reserved supporting body and the backfill supporting body, the combined arch walls are characterized with asymmetric property, coordinate deformation property and hierarchy. And on the basis of the rock rheology and timeliness strength, the instability criteria for weak-layered slopes are provided here. By applying unloading analysis system and the numerical simulation software, we probed into the unloading timeliness length for mining slopes located in Yiminhe surface coal mine as well as the X-axis creep displacement occurring at the slope foot under the influence of unbalanced stress. And based on these facts, we proposed a resource recovery plans specifically drawn up for the slippery areas. The research results indicate the following conclusions: (1) there is a linear relationship between the timeliness length of unbalanced stress unloading and the mining parameters (mining depth and width), so the linear gradient increases with growing mining depth and width; (2) with growing mining parameters, the increase of X-axis creep displacement at slope foot shifts from linear function to quadratic function; (3) by adopting short working line and intense working face advance, it is highly probable to recover a total amount of 3.5 million tons of coals on condition of stable slope.

Keywords Surface coal mine · Mining slope · Unloading · Timeliness length · Supporting wall model

1 Introduction

According to coal mining scheme, stripping and excavation practice is required in large-scale surface coal mines that are nearly horizontally distributed in China. And the original reservoir stress, under the effect of long-term unloading, has become balanced. However, as the excavation work removes the effective supporting body, in situ stress would consequently goes through another round of unloading and redistribution (Guo et al. 2011; Yang and Liu 2013). Slopes with different strike length demonstrate diverse stress state in their own bodies. For slopes with short strike length, the stress will be transferred to the end sides of the rock, which eventually forms a stress unloading arch in which all the rocks are being compressed and therefore, of high strength, which means the slopes are comparatively stable. On the contrary, for slopes with large strike length, no stress unloading arch takes

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shape after the stress redistribution and there would be tensile stress (Chen et al. 2012; Yu et al. 2013) in middle part of slopes. As a result, the tensile stress of rock is weak and the slope stability would be undermined. Since the unloading of unbalanced stress during mining process in the end slope is detrimental to the overall slope stability, studies on the unloading pattern in the mining process is of great significance to the end slope stability, as well as the inner dumping with burying slope.

The basic working patterns of short working bench (Cai et al. 2008), mining by areas and inner dumping with burying slope are widely adopted in China large-scale surface coal mines that are nearly horizontally distributed. Working slope, end slope and working slope in internal dump gradually take shape with the process of extending and deepening in the surface mine. And with mining process advancing, the dynamic development of all the slopes in the surface assumes a cycle change. For different areas in surface mine, the mining work can cause, to different extent, the unloading of unbalanced ground stress, which will gradually form compound arch walls in the surface mine.

Compound arch walls in surface coal mines are characterized as: ① Those formed in open pit end-slope are typically asymmetric due to the fact that the physical and mechanical properties, as well as the operating technology are different between surface mining area and the internal dump; ② arch wall deformation of each layer has evident-coordination since the rocks in surface coal mines are sedimentary rocks and the adhesive layer exist amongst arch wall beds; ③ stress state is hierarchically featured, as the basis of layered deformation, damage and instability is horizontal stress state converted from gravity through Poisson effect, as shown in Fig. 1.

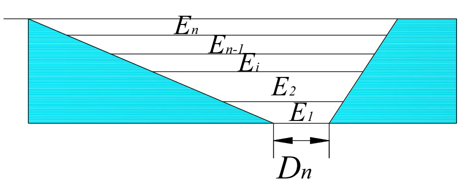

Fig. 1 Model of asymmetric combined arch wall in surface mine slope

2 In-Situ Rock Stress and Excavation Unloading

2.1 In-Situ Rock Stress

In-situ rock stress is natural stress existing in the earth crust before being affected by engineering, and is also called rock mess initial stress, absolute stress or ground stress (Shi et al. 2011; Zhang et al. 2013). In broad sense, in situ rock stress also refers to the stress inside the earth, including stresses produced by geotherm, gravity, earth rotation speed and other factors.

In the case of relatively shallow burial depth of surface coal mines, in other words flat seams, ground stress is mainly caused by gravity effect. Under the condition of horizontal ground, vertical stress on the unit body with a depth of H is σ_z, the weight exerted on unit body (shown in Fig. 2) by overlying strata and it can be calculated using Formula (1).

$$\sigma_z = \gamma H \tag{1}$$

In the above formula, γ is bulk density of overlying strata, measured in kN/m^3; H stands for the burial depth of rock mess unit, measured in m.

According to Poisson effect, horizontal stress σ_x and σ_y at the depth of H are:

$$\sigma_x = \sigma_y = \lambda\gamma H \tag{2}$$

In formula (2), λ means the lateral pressure coefficient.

And

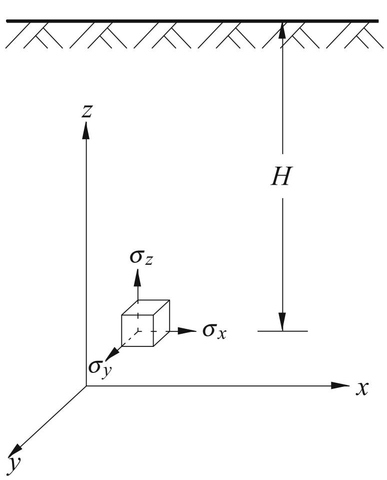

Fig. 2 Gravity stress of rock mass

$$\lambda = \frac{\mu}{1-\mu} \tag{3}$$

In formula (3), μ is Poisson ratio.

As rock Poisson ratio μ is generally 0.2–0.3, vertical stress σ_z, horizontal stress σ_x and σ_y are all principal stress in the self-weight stress field of rock mess with the horizontal stress accounting for 25%–43% of the vertical one. When burial depth increases, self-weight stress of rock mess will exceed its elastic limits and turn out to be apparent plasticity. Especially under high temperature and pressure, hard and brittle rock mess will gradually change to be of plasticity, which makes lateral pressure coefficient around 1.0, a hydrostatic pressure state.

2.2 Excavation Unloading

According to the distribution of in situ rock stress, since the special circumstance of rock layers has been selected for analysis, and the comprehensive rock stress and the Poisson effect on the rock are synthesized as well, the model for analyzing the unbalanced stress can be established. Since the furrow surface mine is a pit resembling an inverse prismaid formed by excavating on original ground surface (Fang and Wu 2013), shown in Fig. 3, the rock existing in each layer is stressed from six directions, which are illustrated as follows: the extruding stress F_d applied on the end sides of the bench by end slope; the pressure P on the top coming from the overlying benches; the supporting stress N on the bottom applied by the lower benches; the extruding force F_n at the rear applied by the initial rock; the supporting stress F_n' in front applied by the unexcavated rock. The structure model is specifically shown in Fig. 4.

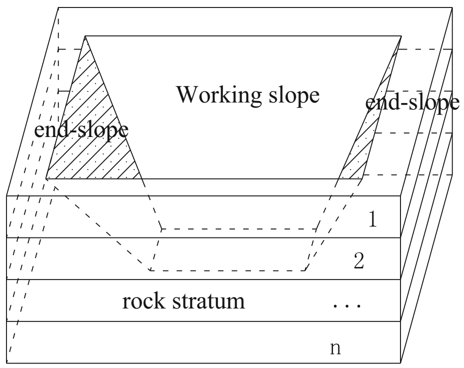

Fig. 3 Excavation model in surface coal mines

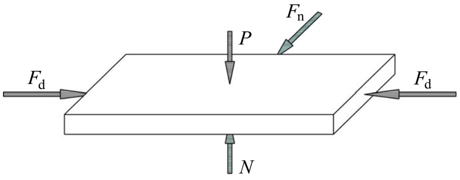

Fig. 4 Stress analysis for rock stratum

Once rocks in the mining areas are removed during the mining process, there would be no effective supporting stress in the mining areas, which eventually leads to the disappearance of F_n'. As a result, an unbalanced stress system is produced as in Fig. 5.

After excavation, stress from the other four directions still remains a balanced state. When F_n' has disappeared, the extrusion pressure F_n, which is applied on the benches of end slope, is converted from the ground stress in the rock body through Poisson effect. In this case, cohesive force and friction force in the rock are supposed to balance the F_n. With the long-term effect of F_n, there would be certain displacement for rocks towards mined-out areas resulting from its rheological properties. And when F_n grows to be great enough and goes beyond the viscous effect of rock mass itself, landslides will easily occur then.

3 Unloading Arch Model of Excavation and Study on Unloading Features

3.1 Unloading Arch Model

Slopes would go through constant deformation under unloading effect from ground stress after excavation. The hypothesis is made that the ground stress within the slope in surface mine is constant and direction is the same. Layered sedimentary rocks (Wang et al. 2013) mainly constitute surface mine slope. Different

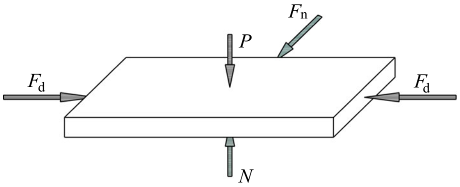

Fig. 5 The sketch of unbalanced stress analysis after excavation

layers associate with each other and form layered beams inside sliding bodies. Therefore, end-slope unloading can be seen as combined beam unloading, with mining area and internal dump regarded as two fixed fulcrums. And the mechanics model is shown in Fig. 6.

Normal stress σ of any point in the beam is known as follows:

$$\sigma_i = \frac{M_i y_i}{J_{zi}} \tag{4}$$

In Eq. (4), M_i is the bending moment of that point in layer i, measured in N m; y_i is the distance from layer i to neutral axis of the section, measured in m; J_{zi} is the section distance from layer i to symmetrical neutral axis, measured in m.

If the beam width is defined as a unit, then the section distance of section is:

$$J_{zi} = \frac{h_i^3}{12} \tag{5}$$

In the above equation, h_i is the thickness of rock mess in layer i, measured in m.

Normal stress of any point in the beam is:

$$\sigma = \frac{12My}{h_i^3} \tag{6}$$

And shear stress of that point is:

$$\tau_{xy} = \frac{3}{2} Q_x \left(\frac{h^2 - 4y^2}{h^3} \right) \tag{7}$$

According to the calculation of clamped beam, the maximum bending moments exist in the two ends of the beam, $M_{\max} = -\frac{1}{12}\sigma_{yi} L_i$, so the maximum tension stress there can be obtained:

$$\sigma_{\max} = \frac{\sigma_{yi} L_i^2}{2h_i^2} \tag{8}$$

where $\sigma_{yi} = \lambda\gamma \sum_i^n h_i$.

According to Fig. 6, we conclude that:

$$l_1 = D_n \tag{9}$$

Suppose that the exposure length of strata floor in layer i is l_i, then:

$$l_{i+1} = l_i + h_i(\cot\phi + \cot\gamma) \tag{10}$$

The average exposure length of layer i strata is:

$$L_i = \frac{l_i + l_{i+1}}{2} \tag{11}$$

If Eq. (10) is substituted into Eq. (11), the following equation can be obtained:

$$L_i = l_i + \frac{h_i(\cot\phi + \cot\gamma)}{2} \tag{12}$$

Based on Eqs. (9) and (12), L_i can be obtained through recursion.

3.2 Excavation Unloading Features

The excavating process of slope is shown in Fig. 7. Originally, stress from left and right sides remain a balanced state in the contact ground layers. When the rock layers between the bilateral end slope lines are removed, which brings about the elimination of supporting force from the stop rock (ShangT and Cai 2006), the initial ground stress will be accumulated on the surfaces of the bilateral end slopes, which is shown in Fig. 7b. This unbalanced stress increases as the depth H grows, by following an obvious linear pattern.

It is supposed that the rock formations are perfectly elastoplastic structures. According to Poisson effect, the longitudinal force will be translated into some degree of lateral strain. Based on these, the unbalanced stress applied on the end slope is:

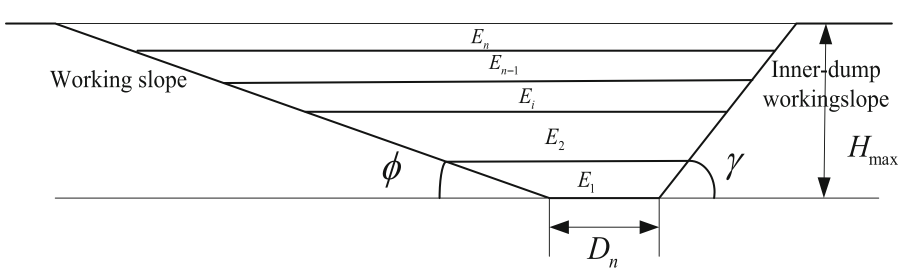

Fig. 6 Composite beam model of slope in surface mines

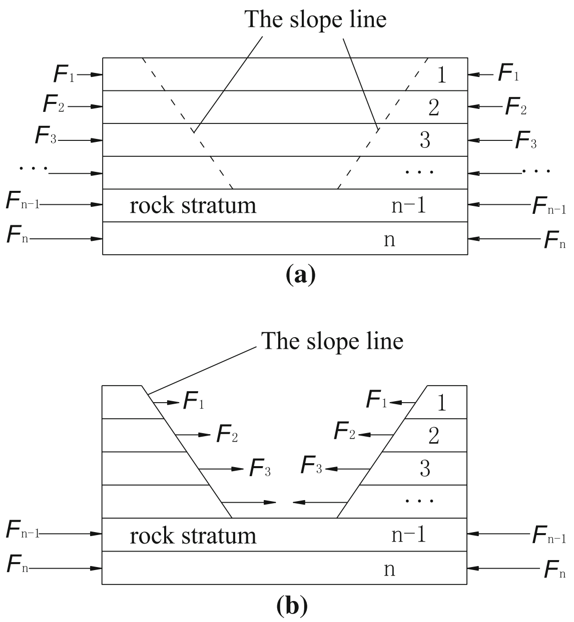

Fig. 7 The schematic diagram of ground stress during excavation unloading

$$F_{\mathrm{n}}=\frac{\mu}{1-\mu}\gamma H \quad (13)$$

As we can see from the Eq. (13), unbalanced stress for the same homogeneous lithology obeys the linear function, that is, the unbalanced stress drops to its minimum value around the ground surface, and reaches to the maximum point at the slope toe of end slope with the depth increasing.

The unloading of unbalanced stress brought about surface mining process applies detrimental influence on the end slope stability. Therefore, both the yielding rate of unbalanced stress and the residual stress are important reference for the slope stability calculation. Once the unbalanced stress is generated, it will be immediately unloaded to gob areas by transferring it onto the end slope rocks, which is shown in Fig. 8. In the case that the cohesive stress and friction stress in the rock are strong enough to offset the unbalanced stress, the following relationship can be deduced:

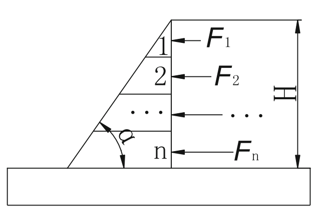

Fig. 8 The distribution rule of stress unloading

$$F_{\mathrm{u}} \leq W \tan \varphi + cl \quad (14)$$

In this equation, W stands for the gravity of overlying rock mass, $W = \sum_{i=1}^{n} \gamma_i S_i$; l stands for the slip plane, $l = h/\tan \alpha$.

In Eq. (14), F_{u} means unbalanced stress, measured in kN; W stands for the gravity of overlying rock mass, measured in kN; γ_i stands for the bulk density of layer i, measured in kN/m^3; S_i is the of the sectional area of layer i, measured in m^2; φ means internal friction angle, in degree (°); c means cohesion, in kPa; l represents the length of slip plane, in m; h stands for the depth of the rock layer, measured in m.

When the rock layers in slope slide, even at an accelerated speed, the viscous effect among rock layers cannot counterbalance the unbalanced stress due to excavation.

$$F_{\mathrm{u}} \geq W \tan \varphi + cl \quad (15)$$

Under long-term effect of the ground stress, the deformation and displacement of end slope accelerate gradually, and when they exceed a certain limit, the structural integrity of slope would be destroyed, followed by landslides.

4 Instability Criteria of Slopes Containing Weak Layers

Suppose that there is key rock layer in strata, and slope key layer refers to the stratum of the worst mechanical properties among strata. If apparent weak layers exist, then the creep phenomenon will emerge in strata. According to aging theory (Rui et al. 1999), general flow equation of weak layers can be expressed as following:

$$\tau = \frac{A_0}{(1+\delta t^{\alpha})}\gamma^m \left(1+\frac{\sigma_m}{[\sigma]}\right) \quad (16)$$

In the above equation, τ is the shear stress exerting on weak layers, in MPa; A_0 is transient shear modulus, measured in MPa; t means shear duration, measured in days; γ stands for shear strain, in percentage (%); σ_{m} is normal stress, measured in MPa; m is strain enhanced factor; δ, α are all experimental constants.

Numerous creep and deformation experiments in weak layers have proved that shear-resistance strength in weak layers reduce with the time prolonging of shear stress effect. Before sliding disasters happened, many underwent a period of time and then experienced instability and damage, especially those caused by strength creep process of weak layers.

Shear stress under instantaneous loading effect in weak layers is called instantaneous strength τ_0. Critical strength of shear stress under long-term loading effect is called long-term strength limit τ_∞. Shear stress, which is between instantaneous strength τ_0 and long-term intensity limit τ_∞ and can cause instability and damage within a certain time, is called long-term strength.

According to the above analysis, we can obtain critical instability criteria of timeliness slope under micro-mechanism:

$$\sigma_{\max} = \tau(t) \tag{17}$$

Then,

$$\frac{\sigma_{yi} L_i^2}{2h_i^2} = \tau(t) \tag{18}$$

According to Eq. (18), we know that control of slope stability 12 can be realized by regulating pit bottom width and slopes of mining areas and internal dump, as well as the slope height of the lowest weak layer, especially.

5 Case Studies

Abundant coal resource exists in the eastern part of Inner Mongolia Autonomous Region in China, and these coal fields are generally characterized with horizontal occurrence, as well as the slope angle of below 10°, hence, surface mining is an ideal solution there. Yiminhe surface mine as a subsidiary of Huaneng Group is located in Ewenkeqi, Hulunbuir city, Inner Mongolia, China, 78 km north from league Hailar city, with the geography coordinate 119°30′–119°50′E and 48°30′–48°50′N. The east-to-west width and the south to north length of this coal field are generally 15 km and 50 km respectively. Yiminhe surface mine was discovered in 1976 and formally went into operation in October 1984. The current advancing direction in Yiminhe surface mine is from south to north, with an annual production of 27 Mt. The physical and mechanical parameters of the major rock layers in end slope are shown in Table 1.

The overburden in Yiminhe surface coal mine is mainly composed of topsoil, quaternary sandy clay, mudstone and sandstone, which are easily affected by water and seismic parameters. The shear strength of this overburden descends sharply 13 when water and seismic parameters are involved, which will lead to the mudding and liquefaction respectively, and the existing slope has shown significant deformation, as shown in Fig. 9. In the water-free state, the hardness of overburden is significantly improved and the multidirectional fissures are well developed, which have enhanced the shear strength to some extent. In this case, the structural type of rock is mainly stratified structure with gentle inclination, which makes it impossible to slide along the surfaces of layers, and its failure pattern is dominated by the circular sliding. In the state of water-existence, the weak layer may produce flow deformation, and the experimental rheological strength of weak layers is shown in Table 2.

5.1 Research on Rules for Timeliness Length of Unloading

If the unbalanced stress goes beyond the viscous effect in the rock, landslide would occur. At this time, the unloading of unbalanced stress is transferred in the new stable slope body after a period of time, which means that the unloading of unbalanced stress in the sliding body has disappeared. When the unbalanced stress due to excavation is less than the viscous effect in the rock, the unbalanced stress will gradually disappear, by which the internal stress in the end slope tends to be at a balanced state. For the research on timeliness length of unloading, the soft for numerical simulation can be adopted instead of quantitative analysis, with which the curve of unloading of unbalanced stress can be recorded, and the consequential statistics analysis can be conducted. According to the excavation process in surface mine, the mining parameters should be adjusted correspondingly, and the timeliness length of unloading with different widths and heights should be compared. Consequently, the regular conclusion for timeliness length of unloading can be summarized.

Table 1 Geological parameters of Yiminhe surface coal mine

Geological parameters	Bulk density (kN/m^3)	Cohesion (kPa)	Internal friction (°)
Sandy clay	19.2	26	17
Mudstone	20.4	34	29
Siltstone	21.1	41	31
Medium Sandstone	22.1	55	35

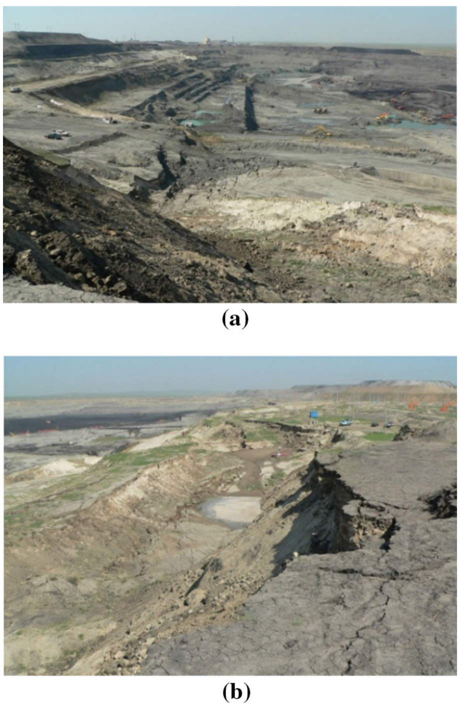

Fig. 9 The current situation of slope at Yiminhe surface coal mine

The slope model is established according to the end slope structure, and the ground stress is initialized in a balanced state. Then the excavating work is carried out. The depth of the excavating pit are 30 m, 60 m, and 90 m respectively, and the width of it is increased gradually from 20 to 80 m by the step of 20 m. The boundary condition of computational model is: 4 fixed displacements on the side and fixed displacement on the bottom surface. The unloading curve of unbalanced stress for each excavation is recorded. As a result, the timeliness length of unloading can be figured out, which is shown in Table 3, and the creep displacement of exposed rock is shown in Table 4.

The cut with 30 m, 60, 90 m depth and the width from 20 to 80 m by 20 m internal was mined, which was shown in Fig. 10. The unbalanced force was recorded in Fig. 8, and the unloading length in Table 2 (Fig. 11).

According to different excavating dimensions and the unloading time of unbalanced stress, the curves in Figs. 12 and 13 are drawn as follows:

As we can see from Table 3 and Fig. 12, once the strip is mined with a fixed width, the time for the unloading of unbalanced stress gradually increases with the growth of mining depth; in case that the mining depth is fixed, as the mining width increases by the same proportion, the time for the unloading of unbalanced stress also performs a good linear growth; the larger the mining width and depth are, the greater the linear gradient will be.

The long-term effect of unbalanced stress on the end slope can cause slow creep in the rock. According to Table 4 and Fig. 13, when the mining depth is fixed, the X-displacement in the slope toe increases gradually with the mining width extending; whereas when the mining depth is small, the X-displacement in the slope toe increases by linear relationship; when the

Table 2 The achievement of mudstone flow deformation experiment

Sample	State of sample	Long-term strength index		Bulk density, γ (kN/m^3)	Moisture content, w (%)
		Cohesion, C (kPa)	Internal friction angle, φ (kPa)		
Mudstone	Original	19.5	8.9	18.2	36.7
Mudstone	Reshaping	22.9	6.2	17.9	45.1

Table 3 The limit timeliness length of unbalanced stress unloading

Width (m)	Depth (m)		
	30	60	90
	Unloading time (s)		
20	0.6	0.8	1.0
40	0.8	1.0	1.3
60	0.9	1.2	1.6
80	1.1	1.5	2.0

Table 4 The X-displacement in slope toe of different excavating conditions

Width (m)	Depth (m)		
	30	60	90
	X-displacement/10^{-2} m		
20	6.0	8.3	9.5
40	6.3	8.4	9.8
60	6.5	8.7	10
80	6.8	9.3	12

mining depth is large, the advancing rate of the X-displacement accelerates, which means when the mining depth increases gradually, the advancing rate of the X-displacement is also accelerated, as a result, the relationship between depth and X-displacement turn out to be quadratic function instead of the linear function.

5.2 The Resource Recovery Scheme

If slope displacement and displacement speed which are obtained under sophisticated monitoring equipment remain almost unchanged, coal bench can be pushed to F43. Then internal dumping can be operated from west to east, and slope toe of spoil would be adjacent to the coal bench in the west. At the same time, next mining panel is started, as is shown in Fig. 14.

In the west, thickness of coal seam is over 22 m. After mining the above two benches, the remaining coal can be excavated at large and then dumping and pressing slope toe are conducted, if slope stability is at a good state. On the contrary, if slope isn't at a stable state, coal seams could be abandoned to guarantee slope stability.

The method in Figs. 15 and 16 could be further applied in 16th coal recovery.

This kind of mining method firstly advances south on the upper bench (standard height 630 m) along 70 m working bench length, and stops advancing when bench slope crest keeps 40 m away from F43

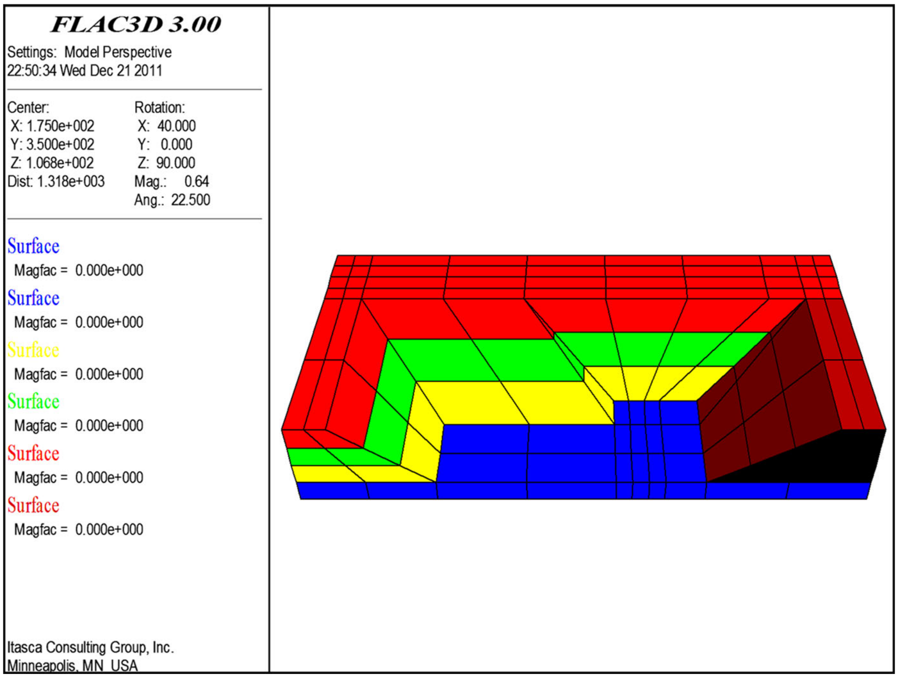

Fig. 10 Slope model for strip steep mining

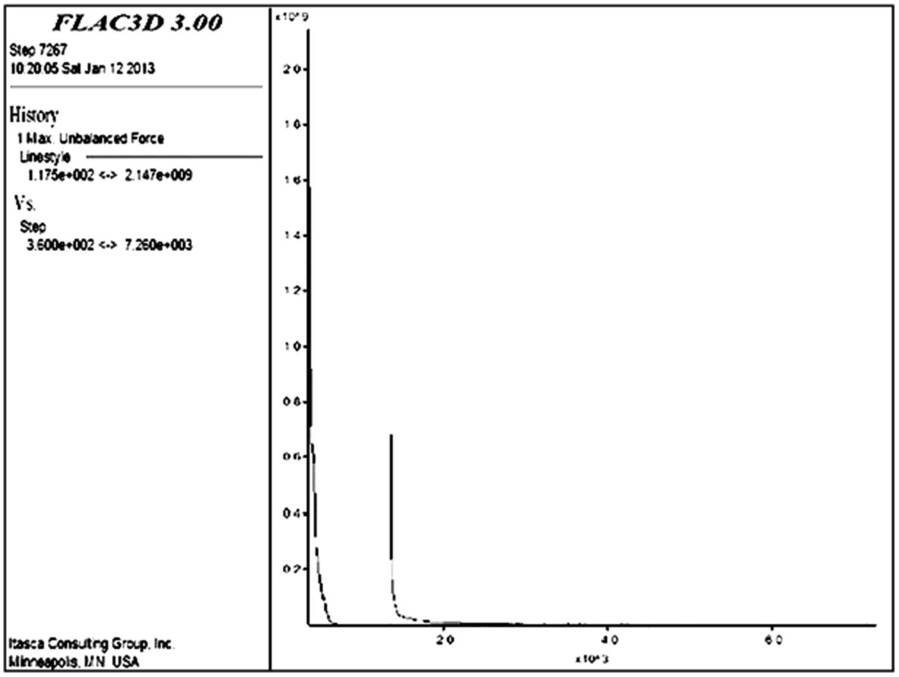

Fig. 11 Stress–strain curve of feature node

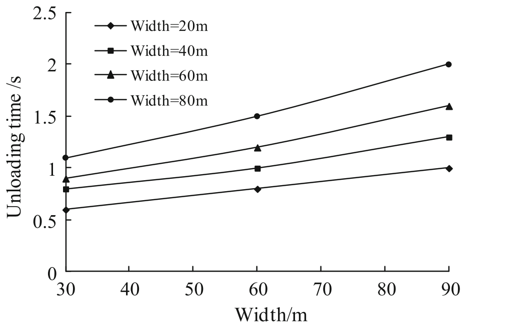

Fig. 12 The curve of relation between excavation depth and unbalanced stress unloading time length

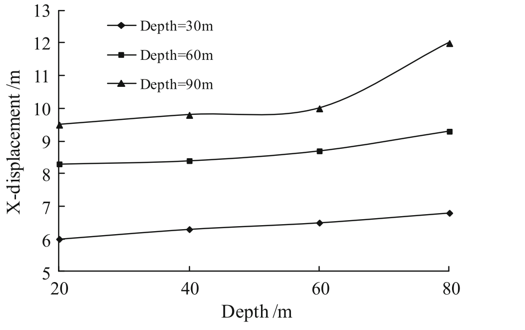

Fig. 13 The curve of relation between excavation depth and X-displacement at slope toe

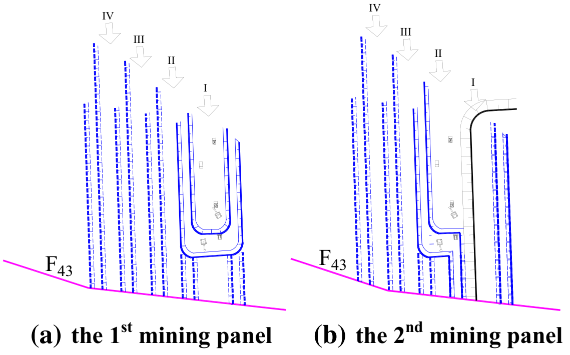

Fig. 14 The 16th coal mining sequence on southeastern slope in Yiminhe mine

fault. Excavating equipment returns to north, and advances south to start the second mining panel along 40 m working bench length. At the same time, lower level (standard height 620 m) recovering mining is conducted with working bench length 40 m. If coal floor 16 is exposed after mining the second level, then internal dumping is followed. If there is remaining coal, and south slope won't slide according to monitoring results, then we can carry on the third bench mining, On-site situation as shown in Fig. 17.

Based on supporting wall model of surface coal mine, the method of short working bench, swiftly advancing and quick backfilling had been adopted in

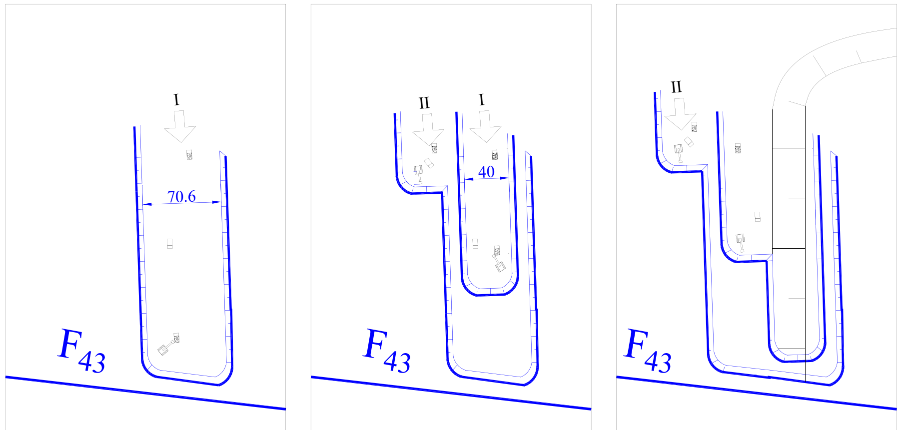

Fig. 15 Another way for mining 16th coal on southeastern slope

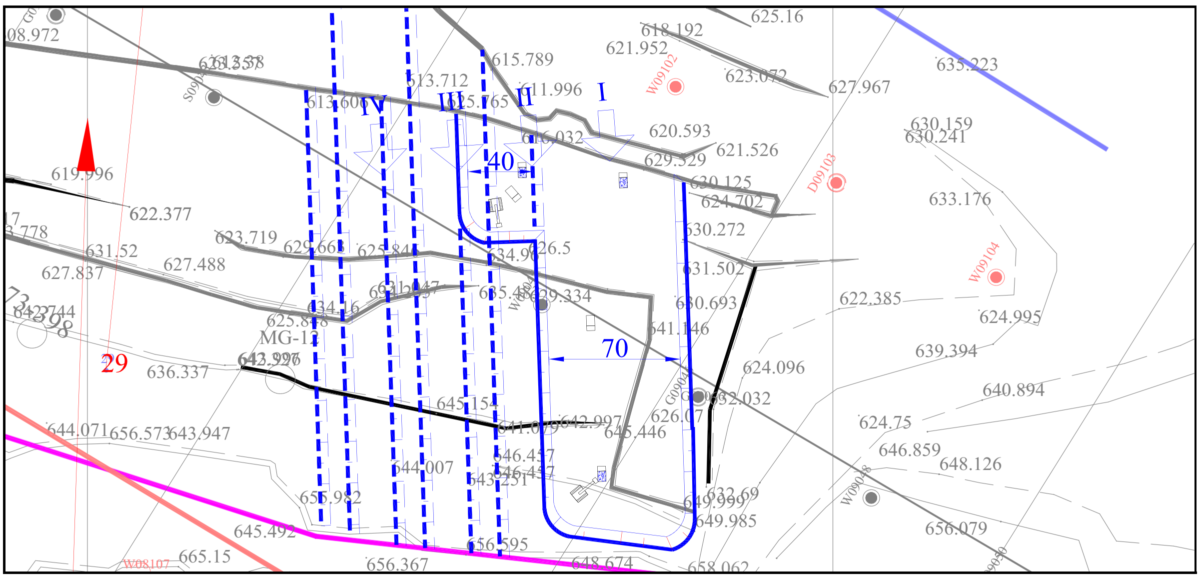

Fig. 16 Enlarged drawing of another plan for mining 16th coal on southeastern slope

the successful coal excavation of over 3.5 Mt (worth of over 350 million RMB and profit of 100 million RMB) in sliding area before March 2009. This not only saves expensive slope fastening expense, but also reduces the influence of landslide control on the surrounding environment and facilities. Stability of internal spoil and covering-wall slope has been greatly improved, avoiding resource waste and guaranteeing surface mine safety, thus good economic and social benefits have been achieved.

Fig. 17 The coal recycling site next to the slippery slope in Yiminhe surface coal mine

6 Conclusions

1. In this paper, the spatiotemporal characteristics of the dynamic development in surface mine was analyzed, and the model for in situ rock stress and unloading was established. The ground stress redistributes in the slopes with different strike lengths, and the unloading arch will be formed by in situ rock stress in the slope with short strike length, as a result, compound arch walls are formed by different unloading arches in diverse rock layers. The asymmetric property, coordinate deformation property and hierarchy of arch walls are analyzed by taking into consideration the difference between reserved supporting body and backfilled supporting body.
2. Based on asymmetric support wall model of finite seam slope in easy sliding area, the timeliness shear strength of weak layers was analyzed. And the instability criteria for slopes containing weak layers were given. The exposure time and flowing confine can be controlled by regulating the mining parameters to ensure the slope stability.
3. The mining work disturbs the integrity of the original rock and leads to the unloading of unbalanced stress which is affected by the parameters such as mining width and mining depth. These two parameters present a very good linear growth relationship, and as they increases, the gradient of the line ascends gradually as well; while the parameters are small, there is a linear relationship between the X-displacement and them, and when they grow up to some extent, the relationship above is replaced by the quadratic function gradually.
4. Method of short working bench, swiftly advancing and quick backfilling is applied in weak layers existing in southeastern end-slope of Yimin surface mine, which has reduced the exposure time and exposed length of mudstone weak layers, and has made it successful to reclaim coal resources of more than 3.5 Mt in sliding area, which is equivalent to a profit of over 0.1 billion RMB. As a result, the swiftly advancing method in the working benches in slippery areas possesses an extensive application value and further enriches the timeliness theory as well as the mining with steep slope theory.

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References

Cai QX, Zhou W, Shu JS, Liu Y, Peng HG (2008) Analysis and application on end-slope timeliness of internal dumping under flat dipping ore body in large surface coal mine. J China Univ Min Technol 37(6):740–744

Chen JJ, Zou YF, Guo WB (2012) Study on the relationship between subsidence coefficient and mining degree under a thick alluvium stratum. J Min Saf Eng 29(2):250–254

Fang XQ, Wu G (2013) Researches on simultaneous extraction of coal and gas in protective layer with a manless working face. Disaster Adv 6(5):200–207

Guo QL, Qiao SF, Liu BC (2011) The movement and deformation of soil and rock mass resulted from mining activity. J Min Saf Eng 28(1):109–114

Rui YQ, Xu XH, Ma XM (1999) Study on non-linear creep property of weak layer in slope of open pit coal mine. J Northeast Univ 20(6):612–614

Shang T, Shu JS, Cai QX (2006) Space-time relationship between end-slope coal extraction and dumping and mining of open- pits. J China Univ Min Technol 35(6):727–730

Shi JX, Liu XR, Liao SB (2011) Analysis of slope stability affected by load of waste dump of mining area. J Min Saf Eng 28(2):258–262

Wang JM, Liu WH, Yang RX (2013) Assessment of the potential ecological risk of heavy metals in reclaimed soils at an opencast coal mine. Disaster Adv 6(3):366–377

Yang PJ, Liu CY (2013) Failure law and control technology of surrounding rock in fully mechanized mining gateway of steep seam. Disaster Adv 6(5):172–181

Yu WJ, Yang JS, Feng T (2013) Global stability evaluation indexes of the filled stope in mining coal mine and example. Disaster Adv 6(4):276–282

Zhang JX, Chen ZH, Tang CA (2013) Numerical simulation study of underground mining influence on pylon foundation stability. Disaster Adv 6(3):451–456