Arch. Min. Sci. **63** (2018), 2, 449-464

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/122458

AIXIANG WU*, SHUNMAN CHEN*#, YIMING WANG*, XUN CHEN*

FAILURE MECHANISM AND SUPPORTING MEASURES FOR LARGE DEFORMATION OF SOFT ROCK ROADWAY IN BALUBA COPPER MINE

MECHANIZM PĘKANIA SKAŁ I KROKI ZAPOBIEGAWCZE PODEJMOWANE W CELU PRZECIWDZIAŁANIA ODKSZTAŁCENIOM CHODNIKA PROWADZONEGO W SKAŁACH MIĘKKICH W KOPALNI MIEDZI BALUBA

To solve the problem of large deformation soft rock roadway with complicated stress condition in Baluba copper mine, the characteristics of roadway deformation and failure modes are analyzed deeply on the basis of geological survey. Combined with the theoretical analysis and numerical simulation, the new reinforcement technology with floor mudsill and grouting anchor cable is proposed. Moreover, the three dimension numerical simulation model is established by the software FLAC-3D, the support parameter is optimized by it. The results show that the optical array pitch of the U-steel shelf arch is 0.8 m, and the optical array pitch of the grouting anchor cable is 2.4 m. At last, the field experiments are done all over the soft rock roadway. Engineering practice shows that the deformation of soft rock roadway in Baluba copper mine is effectively controlled by adopting the new reinforcement technology, which can provide certain references for similar engineering.

Keywords: Soft rock roadway; theoretical analysis; numerical simulation; field experiments; support parameters

W celu rozwiązania problemu powstawania znacznych odkształceń chodnika biegnącego w skale miękkiej w skomplikowanym układzie naprężeń, przeprowadzono dogłębną analizę warunków odkształceń i pękania skał w oparciu o badania geologiczne. W oparciu o rozważania teoretyczne i symulacje numeryczne, zaproponowano nową technologię wzmocnienia progu spągowego z iłowców z linami kotwiącymi osadzonymi w zaprawie. Na podstawie trójwymiarowego modelu do symulacji numerycznych opracowanego z wykorzystaniem oprogramowania FLAC-3D dokonano optymalizacji parametrów podpór. Wyniki pokazują, że optymalne rozmieszczenie stalowych podpór wykonanych z profili w kształcie U wyniesie 0.8 m, zaś optymalny rozstaw mocowań lin wynosi 2.4 m. W końcowym etapie przeprowadzono eksperymenty terenowe na całej długości chodnika. Praktyka inżynierska wskazuje, że odkształcenia chodników prowadzonych w skałach miękkich w kopalni Baluba mogą być skutecznie

* KEY LABORATORY FOR HIGH EFFICIENT MINING AND SAFETY IN METAL MINE, MINISTRY OF EDUCATION, SCHOOL OF CIVIL AND RESOURCES ENGINEERING, UNIVERSITY OF SCIENCE AND TECHNOLOGY BEIJING, BEIJING 100083, PR CHINA

Corresponding Author: shunman_chen1989@sina.cn

kontrolowane poprzez zastosowanie nowej metody wzmocnienia, która stanowić może podstawę dla opracowywania skutecznych technik wzmacniania stropu w chodnikach prowadzonych w podobnych warunkach geologicznych.

Słowa kluczowe: chodnik prowadzony w skałach miękkich, analiza teoretyczna, symulacje numeryczne, eksperymenty w terenie, parametry podpór stropu

1. Introduction

With the development of China, the requirement of minerals is increasing so fast, the underground mine occupy majority of all the mines, but many roadways are easily affected by the mining activity (Guo et al., 2012; Xu et al., 2007). Due to high in-situ stress, mining depth, complicated geological conditions, dynamic pressure and tectonic movements, roadways have undergone severe deformation (Lin et al., 2011; Zhao et al., 2012). The surrounding rock shows the characteristics of obvious soft rock, forms the high in-situ stress soft rock roadway (Fang et al., 2009). According to the current situation of soft rock roadway, it is not easy to guarantee the long-term stability of the soft rock roadway. Good practice indicates that more than 40% of soft rock roadways should be repaired for several times so as to guarantee its stability (Meng et al., 2016; Yu et al., 2015). Thus, the soft rock roadway in the complicated stress condition is one of the pressing issues at home and abroad.

In order to solve the large deformation of such soft rock roadways, many theoretical analysis, numerical simulation and engineering practice have been studied by many researchers at home and abroad. Wang et al. argued that the main reason for the failure of the roadway is due to the active pressure, low strength of the surrounding rock and improper original support method (Wang et al., 2011). He et al. summarized the causes of supporting the failure of deep, soft rock roadway as follows: low strength of wall rock, inadequate support, water effect, and structure stress effect (He et al., 2007). Wang et al. discussed the failure mechanism of the roadway with loose and fractured surrounding rock, also he proposed the section anchor-grouting reinforcement technology method (Wang et al., 2016). Yang proposed the double-layer coupling support schemes to solve the problem of one soft rock roadway on the basis of in-situ test, theoretical analysis and geological survey (Yang et al., 2015). Bai et al. discussed the supporting principle of the high stress roadway, which provides the theoretical basis for roadway supporting (Bai et al., 2008). Yang et al. used the numerical simulation technology to analyze the stability of the roadway, which can provide scientific guidance for safety production (Wang et al., 2013). Li proposed the coupling support of yielding shell to the high stress roadway (Li et al., 2014). Zhang et al. had done a lot of geological survey, by classified the rock mass of the roadway, he put forward the corresponding controlling schemes aiming at different conditions of the roadway, that is the high strength, high pretension force and high stiffness bolting technology, which can provide some guiding for other similar engineering (Zhang et al., 2009). All of these research results can solve the problem of soft rock roadway to some extent, but because of the complexity of the soft rock condition and surrounding rock characteristics, the roadway in different conditions shows different failure characteristics. Special supporting method should be adopted according to different characteristics of soft rock roadway in the complicated stress condition (Ma et al., 2014).

With the progress of mining in Baluba copper mine, the main haulage roadway have undergone large deformation, it has been repaired for several times, but there is still an increasing trend of the deformation. Thus, theoretical analysis, in-situ geological survey, numerical simulation and field experiments are applied to solve the large deformation of the roadway. By the in-situ geological survey, the deformation mechanism of the roadway is revealed. Combined with theoretical analysis, the new reinforcement technology is proposed, and the support parameters are optimized by the numerical simulation, the field experiment results show that the new support method can effectively solve the supporting difficulties.

2. Background

The Baluba copper mine is located in the country of Zambia, with the large production of mines every year. According to the exploit technique conditions, the designed levels of the main haulage roadways are –245 m, –480 m and –580 m. The level –480 m and –580 m are the main haulage roadway levels at present. In order to minimize the operation cost, the central haulage roadways are located in the middle of the ore pillar (as shown in Fig. 1). As the exploitation range increases, the stress shifts to the pillar gradually, with the influence of blasting and underground water, the pillar and roadway undergo severe deformation. Then the roadways were repaired by the U-steel shelf arch and sprayed concrete, but the deformation can't be controlled effectively, it is needed to seek a new support method to guarantee the stability of the roadway.

The semicircular arch cross section is applied for the main haulage roadway in Baluba copper mine, the height and width of it are 3500 mm and 3600 mm, respectively. The surrounding rock of the roadways on level –580 m is mainly composed of argillaceous quartzite, basal conglomerate, dolomitic schist, argillite, etc., which by nature is soft. The main deformed zone is composed of dolomitic schist. Under the influence of high in-situ stress, blasting and ground water, the roadway is severely deformed.

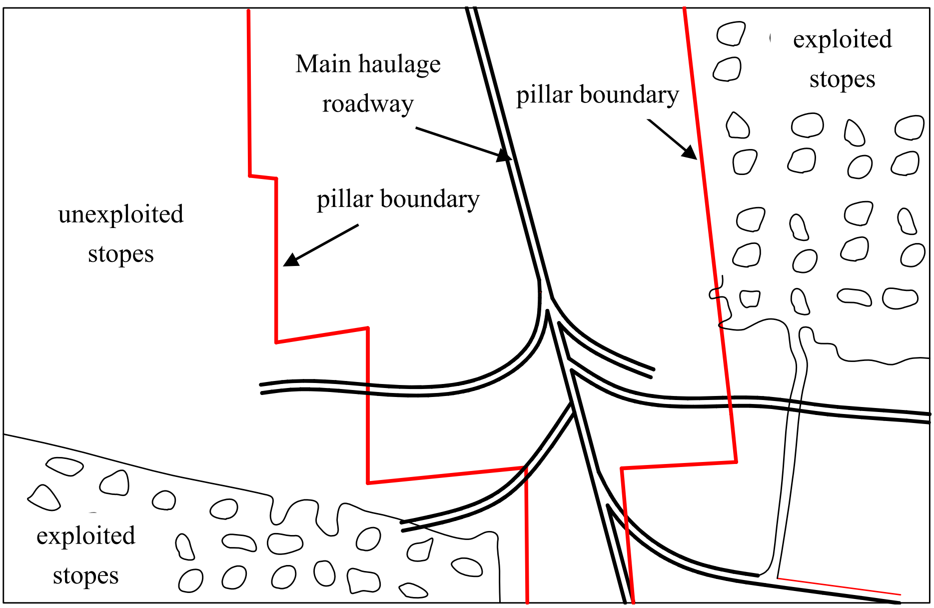


Fig.1. Distribution of the main haulage roadway on 580 m level

3. Deformation characteristics and failure mechanism of soft rock roadway

3.1. Deformation characteristics of the roadway

The roadway has been repaired for several times, there is still an increasing trend of the roadway deformation, therefore, it becomes a serious threat to mine safety in production. According to field investigation, the specific deformation characteristics of the roadways are lists as follows:

(1) The deformation of the roadway is serious. Based on field monitoring, the general convergence and deformation of the roadway is more than 300 mm. Besides that, the failure is mainly induced by large horizontal and lateral pressures. The U-steel shelf arch is twisted and destroyed with large deformation in the short time (as shown in Fig. 2). Floor heave is serious and the deformation of the side walls is severe.

(2) The deformation speed develops too fast. The buried depth of the deformed roadway is 580 m, according to the field survey of the in-situ stress, there exists the high in-situ stress all over the deep mining. The initial support method is U-steel shelf arch and sprayed concrete, as shown in Fig. 3, by monitoring the deformation of the roadway for 60 days, the deformation rate is more than 4 mm/d, moreover, there is still an increasing trend of the deformation rate.

(3) The roadway has the characteristics of time-dependent. The deformation failure occurs after 2 months of completion. The deformed roadway is composed of dolomitic schist, because of the rapid creep, it still has large deformation with time, various supporting technologies have been adopted but failed. The deformation of roadway shows a trend of fast increase, it can be seen that the U-steel shelf arch is under stress obviously.

(4) A cross section of the roadway shrinks. Compared the deformation before and after deformation, the original cross section of the roadway is a semicircular arch, while the

Fig. 2. Failure condition of the main haulage roadway

cross section is a irregular semicircular arch, its left side and right side is asymmetric. The height and width of the roadway before deformation is 3500 mm and 3600 mm, respectively. While the height and width of the roadway after deformation is 3200 mm and 3100 mm, respectively. This is because the geological condition of the roadway is complicated.

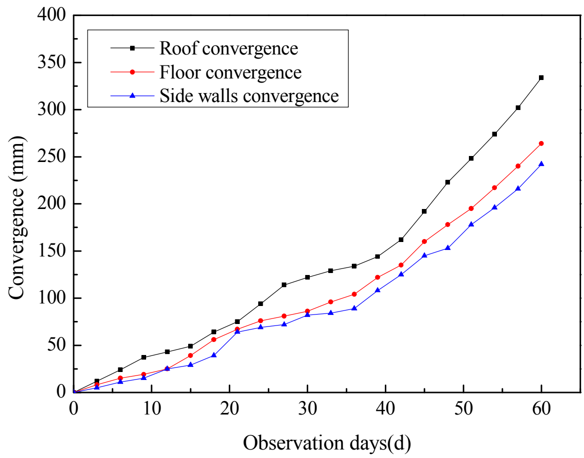


Fig. 3. Roadway deformation observations

3.2. Reasons of deformation failure

According to the field investigation of the deformed roadway in the Baluba copper mine, the main influencing factors causing the large deformation of the roadway can be identified as follows:

(1) Stress concentration. As the buried depth of the deformed roadway is 580 m, the density of the rock is 2500 kg/m^3, so the overburden stress is 14.5 MPa, which is large. When the roadway experiences the large deformation, the U-steel shelf arch tends to be yielding and twisted, inducing the large deformation of the roof, and even caving or failed. The orebody has been excavated above 50 to 100 m of the haulage roadway, the orebody is also excavated on both sides of the roadway, so the original rock stress redistribution occurs. While the haulage roadway on the level 580 m becomes to be the area of stress concentration. Especially in the area within the orebody, which leads to the instability of the haulage roadway. Moreover, it would be more obvious when excavating the residual ore near the haulage roadway.

(2) Low strength of the surrounding rock. The lithology of surrounding rock mainly consists of argillaceous quartzite, basal conglomerate, dolomitic schist, argillite, which has a low resistance capacity to deformation, and its compressive strength and shear strength is low, so it can't bear the tensile stress, and it is easy to expand with water infiltration.

(3) Ground water. The ditch is excavated along the haulage roadway, which is used for draining water. The whole section of the roadway is seriously affected by the water. Not only the conglomerate has the characteristics of hydration and it is easy to be muddy in

leaching, but also the filling between rock joints has the characteristics of expansion. Because of the ground water, on the one hand, it induces the decrease of strength and bearing capacity. On the other hand, the surrounding rock expands, while the strength decreases significantly, leading the roadway in the condition of unstable.

(4) The original support method cannot match the large deformation of the roadway. In the early stage of the construction, the deformation speed is too fast. Moreover, there doesn't exit a detailed exploration of the geological condition. First, its strength is too low of the surrounding rock. Second, the passive method of U-steel shelf arch and sprayed concrete are adopted in the original support, which can't bear the large overburden stress.

According to the field investigation and analysis, although the combined method of U-steel shelf arch and sprayed concrete are adopted on the roadway, the deformation is still large, if effective measures don't be taken immediately, the deformation will be larger, and leading to the destroy of the whole roadway.

4. Theoretical analysis

4.1. Equivalent radius calculation

As it is well known that it is complicated to calculate the straight wall semicircle arch using the complicated analytic function, but it can significantly simplify the calculation process by adopting the equivalent radius. If circumcircle radius is instead of the plastic zone radius, the result is relatively conservative, meanwhile the analytic method solution is relatively complicated. Thus, the "equivalent radius" is adopted to calculate the radius of semicircle arch roadway, the formula of "equivalent radius " is presented as follows (Yu et al., 2015):

$$R_0 = \left(\frac{S}{\pi}\right)^{\frac{1}{2}} \tag{1}$$

where R_0 is the virtual roadway equivalent radius, m; S is the sectional area of the actual roadway, m^2.

With the height and width of 3500 mm and 3600 mm, respectively, the cross section of the main haulage roadway is semicircle arch. So the sectional area of the roadway is 11.56 m^2, the virtual roadway equivalent radius is 1.91 m. In addition, in order to fully reflect the shape effect of underground roadway, a certain correction coefficient is needed for the calculation, then equivalent radius of the roadway can be expressed as follows (Yang et al., 2014):

$$R = k \times R_0 = k \times \left(\frac{S}{\pi}\right)^{\frac{1}{2}} \tag{2}$$

where R is the roadway equivalent radius, m; k is the correction coefficient, the correction coefficient can be obtained as shown in Table 1, the k is 1.1 in this design. Using the formula (2). the equivalent radius of the roadway is calculated, so the equivalent radius of the main haulage roadway is 2.17 m.

TABLE 1

Correction coefficient of different sections of roadway

Section shape	Ellipse	Arch	Square	Trapezia	Rectangle	Inclined trapezia
Coeffecient	1.05	1.10	1.15	1.20	1.20	1.25

4.2. Surrounding rock stress and distribution of plastic zone

The extent of the main haulage roadway is long, so the main haulage roadway can be simplified as the plane strain problem. The mechanical model of the plain strain main haulage roadway is shown in Fig. 4, the H is the height of the overburden surrounding rock, this model is on the basis of the following assuming: (1) As the surrounding rock is elastic-plastic material, it should be regarded as the completely homogeneous continuous elastomer. (2) The cross section of the main haulage roadway should be equivalent to the circle cross section. The stress distribution function of the equivalent roadway is shown as follows (Cao et al., 2014):

$$\sigma_r = \frac{p}{2}\left[(1+\lambda)\left(1-\frac{R^2}{r^2}\right)+(1-\lambda)\left(1-4\frac{R^2}{r^2}+3\frac{R^2}{r^4}\right)\cos 2\theta\right]+p_0\frac{R^2}{r^2} \tag{3}$$

$$\sigma_\theta = \frac{p}{2}\left[(1+\lambda)\left(1+\frac{R^2}{r^2}\right)-(1-\lambda)\left(1+3\frac{R^2}{r^4}\right)\cos 2\theta\right]-p_0\frac{R^2}{r^2} \tag{4}$$

where σ_θ and σ_r are the circumferential stress and radial stress of the main haulage roadway surrounding rock, MPa; p is the equivalent vertical stress or the overburden stress, MPa; θ is the polar angle, °; R and r are the equivalent radius and polar radius of the main haulage roadway, m; λ is the side pressure coefficient; p_0 is the supporting force, MPa.

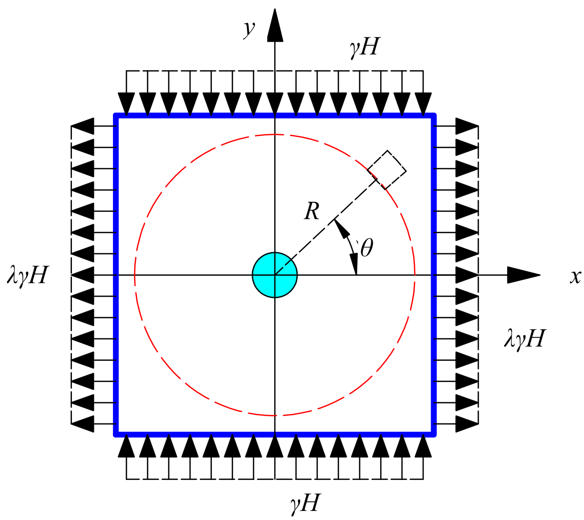


Fig. 4. The circular roadway stress model under different stresses

According to Hoek-Brown strength criterion, it can be obtained as follows (Xu et al., 2006):

$$\sigma_\theta = \sigma_r + \sigma_c \left(\frac{m_b}{\sigma_c} \times \sigma_r + s \right)^\alpha \tag{5}$$

where σ_c is the compressive strength of rock mass, MPa; m_b and s are the Hoek-brown parameters of rock mass; α is constant, and it is determined by the characteristics of rock mass.

By considering different geological conditions, Hoek proposed the method to determine the parameters of m_b and s, the formula is shown as follows:

$$m_b = m_i \exp\left(\frac{GSI - 100}{28 - 14D} \right) \tag{6}$$

$$s = \exp\left(\frac{GSI - 100}{9 - 3D} \right) \tag{7}$$

$$\alpha = \frac{1}{2} + \frac{1}{6}\left(e^{-GSI/15} - e^{-20/3} \right) \tag{8}$$

where D is the disturbance coefficient of rock masses, it ranges from 0 to 1, which is determined by the blasting damage or effect of stress release; GSI is the geological strength index, the range of it is from 0 to 100.

Because the continuations on the elastoplastic, so the critical stresses are equal, by uniting the formula (3)-(6), it can be obtained as follows:

$$\begin{aligned}
&\frac{p}{2}\left[(1+\lambda)\left(1+\frac{R^2}{r^2}\right) - (1-\lambda)\left(1+3\frac{R^2}{r^4}\right)\cos 2\theta \right] - p_0 \frac{R^2}{r^2} \\
&= \frac{p}{2}\left[\begin{array}{c} (1+\lambda)\left(1-\frac{R^2}{r^2}\right) \\ +(1-\lambda)\left(1-4\frac{R^2}{r^2}+3\frac{R^2}{r^4}\right)\cos 2\theta \end{array} \right] + p_0 \frac{R^2}{r^2} + \\
&+\sigma_c \times \left\{ \begin{array}{l} \dfrac{m_i \exp\left(\dfrac{GSI-100}{28-14D}\right)}{\sigma_c} \times \left\{ \dfrac{\mathrm{p}}{2}\left[\begin{array}{c} (1+\lambda)\left(1-\frac{R^2}{r^2}\right) + (1-\lambda) \\ \left(1-4\frac{R^2}{r^2}+3\frac{R^2}{r^4}\right)\cos 2\theta \end{array} \right] + p_0 \dfrac{R^2}{r^2} \right\} + \\ +\exp\left(\dfrac{GSI-100}{9-3D}\right) \end{array} \right\}^\alpha
\end{aligned} \tag{9}$$

According to the field investigation, the GSI of the dolomites schist is 65, the disturbance coefficient of rock mass is 0.7, the compression strength of dolomitic schist is 17.28 MPa, the equivalent vertical stress is 14.5 MPa, the side pressure coefficient is 1.2, so in the process to increase θ from 0 to 360 degrees, the plastic zone distribution of soft rock roadway is shown in Fig. 5, it can be seen that the plastic zone distribution is symmetrical. Moreover, the range of the plastic zone is large, the plastic zone width of the roof, side walls and floor are 2.7 m, 2.9 m and 2.7 m, respectively. The results show that the plastic zone distribution of two side walls is the maximum., and followed by the roof and floor. According to the computational formula, the uniform supporting force is applied to it, actually there is no supporting on the floor, so the distribution of the plastic zone on the floor should be larger, so the floor supporting should be reinforced.

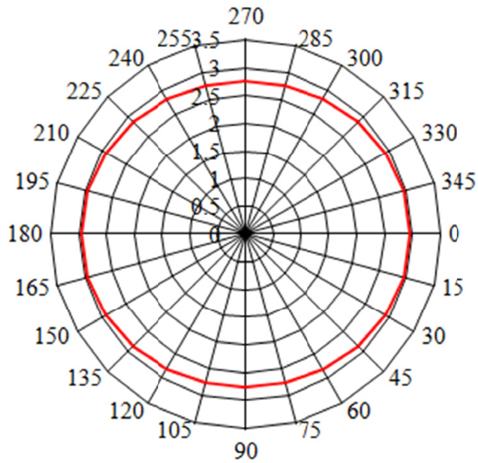


Fig. 5. Plastic zone distribution of soft rock roadway

5. Coupling control countermeasures

5.1. Mechanism of the new support scheme

According to the theoretical calculation, the two side walls and the floor are the main areas to be reinforced, so the floor mudsill and grouting anchor cable are applied to the repair of the soft rock roadway. Firstly, the floor mudsill is the important channel to release stress. Moreover, it is a key factor to influence the deformation of the U-steel shelf arch, the floor mudsill should be used for the reinforcement of the floor. Secondly, the long anchor cable can provide active support, which reduces the deformation of the surrounding rock so as to improve the bearing capacity of the rock mass. For one thing, the anchor cable hole is injected with the slurry, which enhances the strength of the surrounding rock, for another thing, by applying the high pre-stress, the surrounding rock can form the bearing arch (Jing et al., 2005).

5.2. Support method design

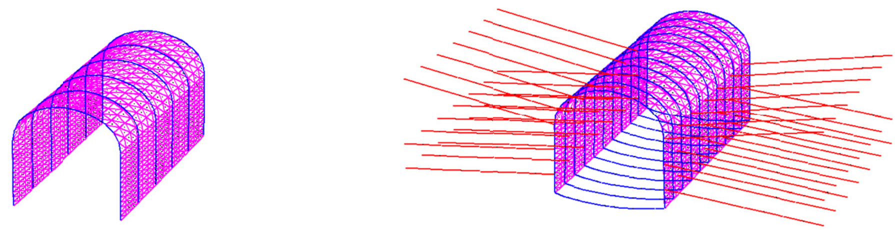
On the basis of the field investigation and theoretical analysis of the soft rock roadway, the main deformation mechanism of the roadway is that the strength of surrounding rock is low, the plastic zone of two side walls is larger than the roof and floor, so the new reinforcement technology of floor mudsill and grouting anchor cable in detail is proposed as follows:

(1) Applying floor mudsill to reinforce the floor. Because the plastic zone area of the floor is too large, the floor is needed to be reinforced. The lap length of the arch floor mudsill and the column leg member should be more than 400 mm, also the lap zone should be fixed. In addition, the welding is used for the connection between the U-steel shelf arch and floor mudsill.

(2) Applying the grouting anchor cable to reinforce the two side walls. The length of the grouting hole is 6 m, cable with a steel strand is used with the diameter of 15.2 mm and the length of it is 6.3 m. The array pitch of anchor cable is 1.2 to 2.4 m, which is needed to be optimized. The double hole anchorage is used, the diameter of the hole is 90 mm. The whole section of the hole is injected with the slurry. The cement ratio is 0.35~0.4. In order to guarantee the strength of the cable, the pre-stress can be applied to the anchor cable after 7 days of grouting. The anchoring force of each cable is no less than 150 kN.

(3) Encryption of the U-steel shelf arch. According to the investigation of the original support scheme, the array pitch of the U-steel shelf arch is 1.6 m, in order to guarantee the stability of the roadway, it is proposed that the array pitch of the U-steel shelf arch can be reduced to 0.8 m.

The new reinforcement scheme of the main haulage roadway is listed above, compared with the original reinforcement scheme, the layout of the original support scheme and new support scheme are shown in Fig. 6 (a) and Fig. 6 (b), and the array pitch of the U-steel shelf arch and anchor cable are needed to be optimized, so five different simulation schemes are proposed to it (as shown in Table 2).



(a) Support mechanics of the original scheme (b) Support mechanics of new schemes

Fig. 6. Support mechanics of roadway

TABLE 2

Schemes of optimized support parameters

Scheme No.	U steel array pitch /m	Anchor cable array pitch /m
1	Original support scheme	—
2	1.6	1.2
3	1.6	2.4
4	0.8	1.2
5	0.8	2.4

5.3. Optimization of the main haulage roadway support parameters

5.3.1. Numerical simulation model

This research mainly studies the repair reinforcement technology of roadway in Baluba copper mine, according to the conditions of the main haulage roadway in Baluba copper mine, the roadway on level -580 m is taken as the typical research target. As there are many software which can be adopted for the simulation of the main haulage roadway in Baluba copper mine, such as ANSYS, PHASE2, FLAC-3D, UDEC, etc., the software FLAC-3D is based on the finite difference program, which is widely used in the underground engineering (Xue et al., 2016), so the software FLAC-3D is selected to optimize the support parameters in Baluba copper mine. The cross section of the main haulage roadway is a semicircular arch, the height and width of the roadway are 3500 mm and 3600 mm, respectively. According to the principle of saint venant, the influence range is about 3~5 times of the roadway's height and width. The model dimension is 30 m×10 m×30 m, that is 30 m long in the X direction, 10 m in the Y direction and 30 m in the Z direction.

According to the load of the overlying burden, 14.5 MPa are applied to the top of model, by investigating the in-situ stress on the field, the horizontal stress is larger than the vertical stress, and it is 1.5 times of the vertical stress. Also the displacement boundary constraints are applied for the model, the bottom of the model is fixed, the displacement in the X direction on the left and right surface is set as 0, the displacement in the Y direction on the pre and post surface is set as 0 (Meng et al., 2013).

As it is shown that the lithology of surrounding rock is mainly composed of argillaceous quartzite, basal conglomerate, dolomitic schist, argillite, etc. In this study, the deformed roadway consists of dolomitic schist, so in this study only the dolomitic schist is considered. By doing experiments in the laboratory, the physical and mechanical parameters of the rock is obtained. Also the geological survey is done, by adopting the Hoek-Brown strength criterion, the parameters of the rock mass can be obtained, which are shown in Table 3.

TABLE 3

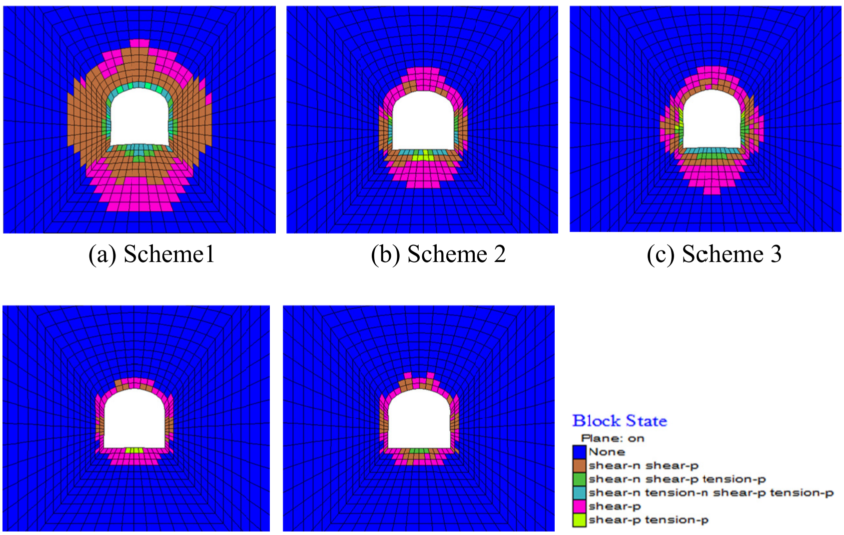
Evaluation results of mechanics parameters of rock mass

Rock type	**Characteristic parameters**					**Rock mass**				
	MR	m_i	m_b	***S***	***a***	**Compressive stress, /MPa**	**Tensile strength /MPa**	***c* /MPa**	***φ* /(°)**	E_{rm} **/(GPa)**
Argillaceous quartzite	450	24	11.16	0.1245	0.500	39.68	7.13	4.34	44.07	16.99
Basal conglomerate	400	20	7.209	0.062	0.500	23.03	4.05	2.45	44.49	8.53
Dolomitic schist	350	8	1.341	0.008	0.502	17.28	2.96	1.79	45.02	3.5
Argillite	500	9	5.4	0.249	0.500	48.61	9.07	5.56	43.28	10.27

5.3.2. Simulation results and analysis

In order to analyze the stability of different support schemes, the slice plane of Y = 5 is set as the typical plane, the distribution of plastic zone with different support parameters are shown in Fig. 7, also the plastic zone radius with different support parameters are listed in Table 4.

As shown in Fig. 7 and Table 4, with the original support scheme, the plastic zone radius of roof, two side walls and floor are 2.54 m, 2.54 m and 3.72 m, respectively. For the new support schemes, the radius of plastic zone on two side walls decreases from 2.54 m to 0.47 m, and the radius of plastic zone on the roof decreases from 2.66 m to 0.58 m, while the floor decreases from 3.72 m to 0.98 m. When the reinforcement of U-steel shelf arch array pitch decreases from 1.6 m to 0.8 m, the radius of plastic zone decreases significantly. However, When the array pitch of the grouting anchor cable increases from 1.2 m to 2.4 m, the plastic zone radius on the two side walls and floor are the same, the plastic zone radius on the roof decreases from 0.91 m to 0.58 m, compared with the plastic zone radius on the roof under original support scheme, there is no obvious influence for the array pitch of the grouting cable increases from 1.2 m to 2.4 m.



(a) Scheme1 (b) Scheme 2 (c) Scheme 3

(d) Scheme 4 (e) Scheme 5 (f) Block's state legend

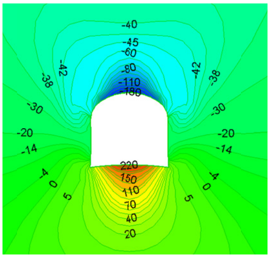
Fig. 7. Roadway plastic zone distribution

TABLE 4

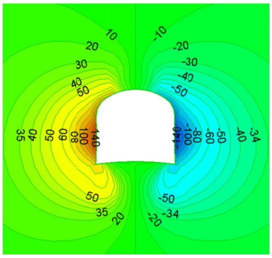
Plastic zone range for different schemes

Scheme No.	Sidewalls/m	Roof /m	Floor /m
1	2.54	2.66	3.72
2	0.74	1.35	2.2
3	1.35	1.35	2.66
4	0.47	0.58	0.98
5	0.47	0.91	0.98

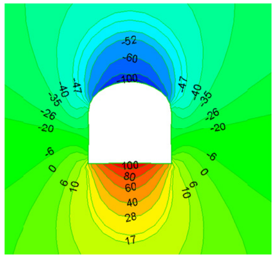
The nephogram of vertical displacement (V-disp) and horizontal displacement (H-disp) with different support parameters are shown in Fig. 8, and the convergence of two sides walls, roof and floor are listed in Table 5. It is evident from the above that the roadway deforms severely with the original support pattern. The convergence of the roof and floor are 195.8 mm



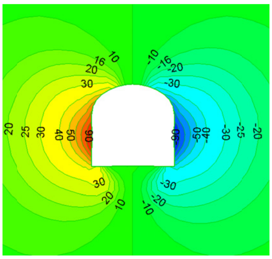
(a1) V-disp of scheme 1



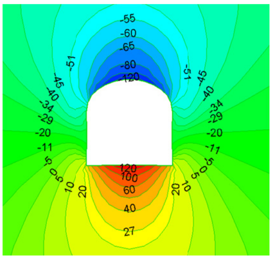
(a2) H-disp of scheme 1



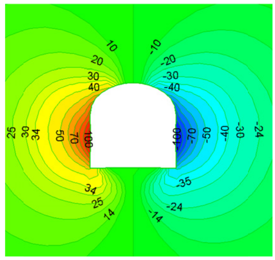
(b1) V-disp of scheme 2



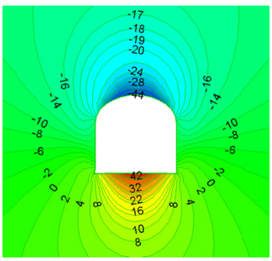
(b2) H-disp of scheme 2



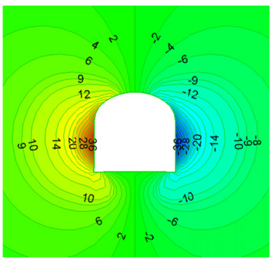
(c1) V-disp of scheme 3



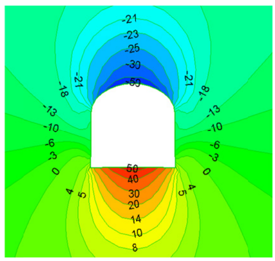
(c2) H-disp of scheme 3



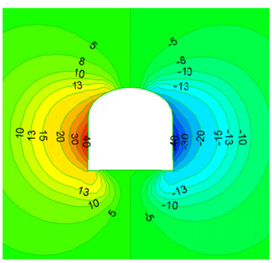
(d1) V-disp of scheme 4



(d2) H-disp of scheme 4



(e1) V-disp of scheme 5



(e2) H-disp of scheme 5

Fig. 8. Displacement of surrounding rock

and 224.9 mm, respectively, while the convergence of two side walls is 153.9 mm. By applying the new support schemes, the deformation of the roadway's surrounding rock decreases greatly. Irrespective of array pitch of the grouting anchor cable, as the array pitch of the U-steel shelf arch decreases, the deformation of the roadway decreases significantly. However, when the array pitch of the grouting anchor cable increases from 1.2 m to 2.4 m, the largest convergences of the roof are 47.5 mm and 54.8 mm, respectively, and the largest convergences of two side walls are 38.3 mm and 44.2 mm, while the largest convergences of the floor are 47.9 mm and 52.1 mm. Hence, according to the comprehensive analysis of displacement distribution and plastic zone distribution of the main haulage roadway for different support schemes, the optical array pitch of the U-steel shelf is 0.8 m, and the optimized array pitch of the grouting anchor cable is 2.4 m.

TABLE 5

Displacement of the main haulage roadway for different support schemes

Scheme No.	Side walls convergence /mm	Floor heave /mm	Roof subsidence /mm
1	153.9	224.9	195.8
2	102.1	105.6	109.2
3	110.1	122.4	117.3
4	38.3	47.9	47.5
5	45.2	52.1	54.8

6. Application and effect analysis

In order to verify the effect of the new reinforcement scheme, the displacement monitoring was done all over the several deformed main haulage roadway, there are 10 monitoring stations all over every monitoring cross section, the space of every two monitoring cross section is 30~50 m. According to the monitoring results, the displacement of the station 1 is the largest, so only the displacement of station 1 is analyzed, the displacement of two side walls, roof and floor is listed in Fig. 9, it can be seen that the maximum convergence of the roof and the floor are 62.44 mm and 58.35 mm, respectively. While the maximum convergence of the two side walls is 50.39 mm.

It is founded that with the new reinforcement scheme, the changing process of the deformation is divided into three phases. The first phase is that the displacement of the main haulage roadway accelerates fast, also the deformation rate is more than 1.0 mm/d, its during time is 0~15 d. Because this phase is just after the new support schemes is implemented, the time is needed for the grouting anchor cable playing a role in the controlling of the roadway. On the second phase, the deformation rate is less than 1.0 mm/d, the deformation increases gradually with time, this stage mainly takes place from 15 to 50 days after adopting the new support scheme, this is because the cement slurry in the anchor cable hole has been solidified, the strength of the surrounding rock increases with time, it indicates that the new support scheme plays an important role in the reinforcement of the main haulage roadway. On the third phase, the displacement remains almost the same value with time, the changing rate of the displacement is nearly stable. This shows that by applying the new support scheme, it realizes the control of the roadway surrounding rock.

In addition, compared with the filed monitoring results and numerical simulation results, it can be seen that the numerical simulation results are consistent with the field monitoring results, the maximum displacement of the two side walls, floor and roof over the deformed main haulage roadway are 50.39 mm, 58.35 mm and 62.44 mm, respectively. While in the numerical simulation, the maximum displacement of the two side walls, floor and roof over the deformed main haulage roadway are 45.2 mm, 51.10 mm and 54.80 mm, respectively. So the results of the numerical simulation and field monitoring are consistent with each other, which shows that the deformed main haulage roadway is effectively controlled by applying the new reinforcement technology.

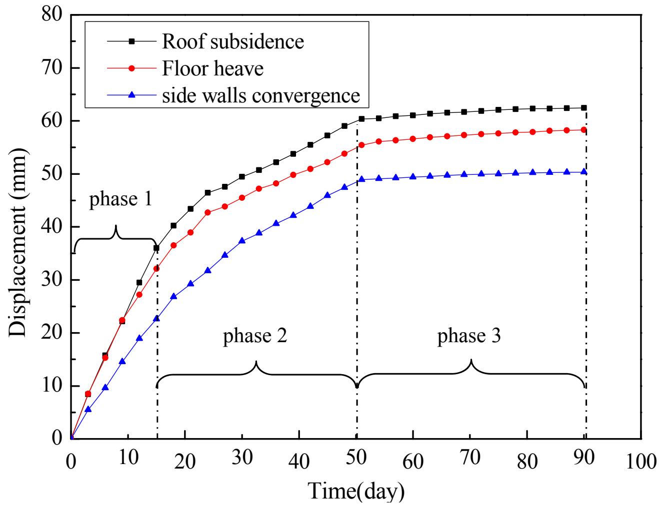


Fig. 9. Displacement of the soft rock roadway

7. Conclusions

(1) By employing field engineering investigation and surrounding rock displacement monitoring, the main haulage roadway presents the characteristics of the following aspects: large deformation of the roof, time-dependent, the roadway shrinks, etc. The main reason of the deformation failure can be concluded as the stress concentration, low strength of the surrounding rock and ground water.

(2) Through theoretical computation and analysis, the plastic zone distribution of the main haulage roadway under original support scheme is obtained, the two side walls and the floor of roadway are the main places which are needed to support, so the new support scheme with a floor mudsill and grouting anchor cable are applying to the repair of the soft rock roadway.

(3) Based on the support mechanism of the new support scheme, by adopting the numerical simulation technology, the array pitch of the U-steel shelf arch and the grouting anchor cable are optimized, the results show that the optimized array pitch of the U-steel shelf is 0.8 m, and the optimized array pitch of the grouting anchor cable is 2.4 m.

(4) Engineering practice indicates that the repaired roadways have not generated roof-caving phenomenon, and the deformation of the main haulage roadway is effectively controlled. The maintenance of roadway roof has been improved significantly, which ensures safety of soft rock roadway in Baluba copper mine, and the new reinforcement technology can provide certain references for similar engineering.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (No. 51574013 and 51674012) and the Fundamental Research Funds for the Central Universities (Grant No. FRP-TP-17-024A1). The authors gratefully acknowledge financial support of the above-mentioned agencies. The authors express their special gratitude to Professor AIXIANG WU, Professor YIMING WANG and Dr XUN CHEN for their constructive comments.

References

Bai J.B., Wang X.Y., Jia M.K., 2008. *Theory and application of supporting in deep soft roadways*. Chin. J. Geotech. Eng. **30**, 5, 632-635.

Cao C., Ren T., Chirs C., 2014. *Introducing aggregate into grouting material and its influence on load transfer of the rock bolting system*. Int. J. Min. Sci. Technol. **24**, 3, 325-328.

Fang X.Q., He J., He J.S., 2009. *Research on reinforced technology for deep soft rock and dynamic pressurized roadway under high stress*. Rock Soil Mech. **30**, 6,1693-1698.

Guo Z., Yang X., Bai Y., 2012. *A study of support strategies in deep soft rock: the horsehead crossing roadway in daqiang coal mine*. Int. J. Min. Sci. Technol. **22**, 5, 665-667.

He M.C., Li G.F., Wang J., 2007. *Study on supporting design for large area serious roof caving of deep soft rock roadway in xing'an coal mine*. Chin. J. Rock Mech. Eng. **26**, 5, 959-964.

Jing H.W., Li Y.H., Xu G.A., 2005. *Analysis of surrounding rock stability of deeply buried roadways and study on its control techniques*. Rock Soil Mech. **26**, 6, 877-876.

Li C., Wang Z., Liu T., 2014. *Principle and practice of coupling support of double yielding shell of soft rock roadway under high stress*. Int. J. Min. Sci. Technol. **24**, 4, 513-518.

Lin H., 2011. *Study of soft rock roadway support technique*. Procedia Eng. **26**, 321-326.

Ma S.Q., Nemcik J.. AzizNaj, 2014. *Simulation of fully grouted rockbolts in underground roadways using FL*. Can. Geotech. J. **51**, 8, 911-920.

Meng B., Jing H., Chen K., 2013. *Failure mechanism and stability control of a large section of very soft roadway surrounding rock shear slip*. Int. J. Min. Sci. Technol. **23**, 1, 127-134.

Meng Q.B., Han L.J., Xiao Y., 2016. *Numerical simulation study of the failure evolution process and failure mode of surrounding rock in deep soft rock roadways*. Int. J. Min. Sci. Technol. **26**, 2, 209-221.

Wang W.J., Peng G., Huang J., 2011. *Research on high-strength coupling support technology of high stress extremely soft rock roadway*. J. China Coal Soc. **36**, 2, 223-228.

Wang F., Zhang C., Wei S., 2016. *Whole section anchor-grouting reinforcement technology and its application in underground roadways with loose and fractured surrounding rock*. Tunnelling Underground Space Technol. **51**, 133-143.

Wang X.Y., Bai J.B., Chen Y., 2013. *Time-dependent laws and initial application of bearing features of bolt-grouting structure in soft rock roadway*. Chin. J. Geotech. Eng. **35**, 3, 469-475.

Xu X.L., Zhang N., Xu J.G., 2007. *Principle and practice of process control over soft broken roadway with high ground stress*. J. of Min. & Saf. Eng. **24**, 1, 51-56.

Xu Z.L., 2006. *Elasticity*. Beijing, China, Higher Education Press, p. 35-55.

Xue Y., Gao F., Liu, X., 2016. *Theoretical and numerical simulation of the mining-enhanced permeability model of damaged coal seam*. Geotech. Geol. Eng. **34**, 5, 1425-1433.

Yang J., Wang D., Shi H., 2015. *Deformation failure and countermeasures of deep tertiary extremely soft rock roadway in liuhai coal mine*. Int. J. Min. Sci. Technol. **25**, 2, 231-236.

Yang T.H., Jia P., Shi W.H., 2014. *Seepage-stress coupled analysis on anisotropic characteristics of the fractured rock mass around roadway*. Tunnelling Underground Space Technol. **43**, 7, 11-19.

Yu Y., Zhu C., Chong D., 2015. *Catastrophe mechanism and disaster countermeasure for soft rock roadway surrounding rock in meihe mine*. Int. J. Min. Sci. Technol. **25**, 3, 407-413.

Zhang N., Wang C., Gao M., 2009. *Roadway support difficulty classification and controlling techniques for huainan deep coal mining*. Chin. J. Rock Mech. Eng. **28**, 12, 2421-2428.

Zhao G.A., Ma Z.A., Zhu Q.C., 2012. *Roadway deformation during riding mining in soft rock*. Int. J. Min. Sci. Technol. **22**, 4, 539-544.