Numerical Simulation of Stress Relief Measures in Exploitation of Deep Deposit in Highly Stressed Zone

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***Abstract*: With the increasing demand of social and economic development of a nation, and the progress of mining engineering technology, the exploitation of mineral deposits is constantly developing to deep which is the inevitable trend of future development. The depth of mining and ground stress have positive relationship, with deep mining, the ground stress increases accordingly. Due to the high concentration of ground stress, rockburst accidents often occur in roadways. The prevention and control of rock burst is very important for the safe mining of deep deposit in high stress zone. According to the physical and mechanical properties of rock mass and characteristics of ground stress in deep deposit of Fankou Lead-Zinc Mine, different stress relief measures are designed for the prevention and control of rockburst. The three-dimensional elastoplastic finite element program is used to simulate and analyze the stress distribution in deep ore deposit of this mine for the purpose of providing basis for deciding to mine and control ground pressure of deep ore deposit in Fankou Lead-Zinc Mine.**

Key words: Deep deposit, Highly stressed zone, Stress relief, Numerical simulation, Rockburst

1. INTRODUCTION

It is obviously known that mineral deposits are indispensable materials for improving the development of a national economy. With the increasing demand of social and economic development of a nation, and the progress of mining engineering technology, the exploitation of mineral deposits is constantly developing to deep which is the inevitable trend of future development. As positively related, the depth of mining increases with ground stress (Liu and Wang 2018). With this deep deposit mining and high concentration of ground stress, the subsequent frequency of rock bursts occurrence increases consequently, which strongly hinder the safe and efficient mining (He et al. 2012; Kaiser and Cai 2012; Chen et al. 2012; Cai 2016; Feng et al. 2017; Sengani and Zvarivadza 2017).

The deep mining has been world widely applied, According to Hudyma and Potvin (2010), Some mines in some foreign countries are working at and greater than 1000m below the ground level, where rock bursts hazards highly tend to occur, for example the deepest mines in Australia are recently working between 1000m and 1650m below the ground surface level; The deepest mines in Canada are working between 1500m and 2500m of depth; and the first wold's country with deepest mines vary from 3000m to 3800m is South Africa (Liu et al. 2018).

In recent years, several metal mines in China have been initiated deep mining greater than1000m below the ground surface level (Liu et al. 2018; Liu and Wang 2018). Some examples of chinese deep mines include Hongtoushan Copper Mine in Fushun, Liaoning province and Shizishan copper mine in Tongling, Anhui province have reached beyond 1000m of

depth (Liu and Wang 2018); Dongguashan Copper (Gold) Mine in Anhui province has also reached beyond 1000m of depth (Shao et al. 2016; Liu et al. 2018; Liu and Wang 2018); Jiapigou Gold Mine in Jilin province, North eastern China, has extended to about 1050 m (Zeng et al. 2014; Meng et al. 2016; Yang et al. 2017); and Xiangxi Gold Mine in Hunan province has been exploited to about 1000m below the ground level (Yang et al. 1998); Shouwangfen Copper Mine in Chengde, Hebei province, has also reached beyond 1000m of depth (Chen et al. 2007); Fankou Lead-Zinc Mine in Guangdong province at 1000m below ground level (zhang et al. 2014); Jinchuan Nickel Mine in Jinchang, Gansu, is working at 1100m below ground level (Yuan et al. 2013; Yang et al. 2017); Rushan Gold Mine in Weihai, Shandong province, has been also exploited to about 1000m below the ground level (Fan et al. 2006).

As deep mine is the rock burst prone area, the occurrence of rock burst in deep mining show multiple and sudden characteristics, and the degree of ground pressure hazards is more serious, which requires a thorough study on the prevention and control of ground pressure hazards in deep mining. In recent years, in addition to strengthening the laboratory research works of mechanical model test and similar material test, some domestic and foreign mining companies have paid more attention to the application of numerical simulation technology in the aspects of rock mass failure mechanism; In the aspect of prediction of ground pressure, continuous improvement is made on the drilling method of pulverized coal and rock mass monitoring technology; In the aspect of prevention and control measures of ground pressure, it is mainly focus on theory and technology equipped with continuous improvement of existing prevention and control measures (Yu et al. 1983; Goodman 1980).

According to the physical and mechanical properties of rock mass and the characteristics of ground stress field in deep deposit of Fankou Lead-Zinc Mine, this paper designs different stress relief measures for rock burst prevention and control, The three-dimensional nonlinear finite element program is used to simulate and analyze the stress distribution in deep ore deposit of this mine for the purpose of providing basis for deciding to mine and control ground stress of deep ore deposit at Fankou Lead-Zinc Mine.

2.THE CHARACTERISTICS OF DEEP DEPOSIT OCCURRENCE

Fankou lead-zinc ore deposit was proved to be one of the china's largest ore deposit (Li et al. 2013). Genesis of Fankou Pb-Zn deposit is stratabound lead-zinc deposit of sedimentary reformed pyrite type. Jinxingling orebody inclines northward, Shiling orebody inclines eastward, and Shiling south orebody is the south extension of Shiling orebody. The orebodies are generally large and medium in size, that is to say, the orebodies above 320m below ground level are thick and large, the orebody between 320m and 470m below ground level is small and scattered, and the orebody between 470m and 650m below ground level is thick. The deep deposits are generally between 360 m and 750m below ground level, and the Shiling orebodies and Shiling South orebodies are between 207 and 218 lines. The Shiling deep orebodies are mainly located in the footwall of fault F3. The proven reserves of the main orebodies Sh209 and Sh2l4 account for 76.9% of the deep proven reserves.

The deep orebody occurs in deep aquifer, and the roof and floor surrounding rocks of the ore-bearing strata are all impermeable layers, In order to avoid the artificial hydraulic connection between deep orebody and aquifer, it is required to fill the goaf in time to ensure that the water-conducting fracture zone of the roof rock does not touch the upper aquifer.

With the increase of mining depth (According to estimation of measured geothermal gradient, the deep rock temperature at 750m below ground level will reach 42℃), the temperature of the surroundings will rise. In deep deposit, there are Lead-Zinc ore which contains high sulfur content and some single pyrite. The ore is oxidable, easy to agglomerate, and liable to heat generation or liable to spontaneous combustion**.** The original rock stress is primarily tectonic stress. According to the actual measurement by Changsha Institute of Mining Research: at 650m below ground level, the maximum principal stress σ1 is 31.2Mpa, the direction is 174.1°, Inclination angle 1.1°; The intermediate principal stress σ2 is 18.8Mpa, direction is 84.16°, inclination angle is -3.31°; Minimum principal stress σ3 is 17.3Mpa, direction is 245.83°, inclination angle is -86.5°. The ratio of the maximum principal stress and vertical stress ranges in 1.02~1.7. The vertical stress value is closed to the dead weight of the overlying rock per unit area. Based on the results of previous studies by Changsha Institute of Mining Research (2004) and deep development observation, it is shown that deep ore deposit and rock mass have the tendency of medium rockburst.

3.THE BASIC THOUGHTS OF STRESS RELIEF MINING IN DEEP ZONE WITH HIGH

There is a positive linear relationship between the mining depth and ground stress which lead to the occurrence of rockburst. Therefore, before thinking about the rockburst prevention and control measures, it is essential to know and understand rock burst mechanism, and then put forward the stress relief measures. Rockburst are seismic events triggered by deep deposits exploitation in which the rocks fail abruptly and brittlely with high degree of damage after getting strained above their ultimate elasticity. According to Larsson (2004), Kabwe and Wang (2015), a rockburst is the exploitation induced seismic event that affects and cause destruction to excavations in the rock. Vennes and Mitri (2017) defined rock bursts as seismic events where the rock suddenly and violently fails in a brittle way after being strained beyond its elastic limit. Previous research results by Mao and Zhang (1996) show that, the rockburst is due to the failure of rock mass balance in high stress zone, and the stress concentration in rock mass causes brittle failure of rock mass and dynamic instability accompanied by energy release. The occurrence of rock burst is controlled by stress conditions, that is to say, the stress in orebody and surrounding rock where rock burst tend to occur should reach the ultimate stress state.

There is a strong linear relationship between the mining depth and rockburst occurrence. With deeply increase of mining depth, the ground stress also is highly increased with decrease in rock strength, which consequently leads to the occurrence of rock burst (Xie et al. 2018). Rockburst is more pronounced in hard rocks and geological features like dykes and faults, and in deep deposits exploitation, it is frequently closely related to deep deposits exploitation techniques leading to unfavorable ground stress condition (Kaiser and Cai 2012). In order to prevent and control rock burst, and realize the safe and efficient mining of deep deposits, the mining engineers can adopt proper mining technology and construction method to improve the stress distribution state and properties of rock mass.

Based on the study of rockburst mechanism and prediction, and how to adopt appropriate mining technology and construction method to mitigate the conditions and occurrence of rockburst disaster, so to achieve safe and efficient mining of deep deposits is the focus of this research. In recent years, the stress relief mining measure has been widely adopted in large and medium scale mines in China and some rest of the world. Stress relief mining is to use stress transfer principle to transfer high stress from the stope to the surrounding area through certain stress relief measures, so as to reduce the stress in the stope or working face, improve the stress distribution of rock mass, and control the overlapping degree of stress increase zones caused by repeated mining effects, therefore, realize safe and efficient mining of deep deposits.

The stress relief mining technology is mainly divided into vertical and horizontal stress relief technology. The vertical stress relief is the partial or total transfer of the overlying strata pressure from the upper part of the stope area to the surrounding area, Under the pressure arch, the mining works only withstand the weight of ore and rock, and the stress value decreases significantly, then becomes easy to exploit. Horizontal stress relief is to isolate the horizontal tectonic stress acting on orebody and form the horizontal stress reduction zone so as to reduce the harm of the horizontal stress (Jie 1992).

4. NUMERICAL SIMULATION OF STRESS RELIEF MINING IN HIGHLY STRESSED DEEP ZONE

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4.1. Design of pressure relief mining scheme

The mining method of deep orebody in Fankou Lead-Zinc Mine is panel mechanized upward high slice cut and filling method, and panel is the basic unit of production operation. The panel is arranged along the direction of orebody, the length of the panel is 80-100m, and there are 8-10 stopes, which are divided into rooms and pillars.

According to the deep ground stress data of Fankou Lead-Zinc Mine, the maximum horizontal stress is 1.02-1.7 times the vertical stress. The horizontal tectonic stress plays a crucial role in the stability of stope. Therefore, stress relief mining plans to divide the panel into stress relief stopes and normal stopes. The stress relief stopes are located on both sides of Panel, ahead of normal stopes, and filled with cemented tailings whose stiffness is lower than that of rock material, so as to reduce the influence of horizontal tectonic stress on each stope within the panel. That is to say, the common upward horizontal slice cut and filling method is used to recover the stopes at both ends of the panel, and the cemented filling with high strength tailings after mining is used to reduce the stress on each stope within the panel during mining, and reduce the possibility of rockfall and rock burst in the stope. On this basis, it can also be combined with bottom drawing or roof cutting and other stress relief measures.

Based on this, four simulation calculation schemes of stress relief mining within the panel are designed. Scheme 1: is to relieve the stress relief stope on both sides of the panel; scheme 2: To relieve the stress relief stope on both sides of the panel, and to carry out the bottom drawing in advance in the stope within the panel; scheme 3: To relieve the stress relief stope on both sides of the panel, and to carry out the bottom drawing in advance in the stope within the panel, and cut the roof in advance, and then backfilled with reinforced concrete after cutting the roof. scheme 4: Only bottom drawing and roof cutting in the panel, and the roof cutting is backfilled with reinforced concrete to make a comparative analysis with the previous plan.

According to the simulation results of stress relief mining in the panel, the simulation calculations of independent stress relief in the single middle section, simultaneous stress relief in two middle sections, simultaneous stress relief in three middle sections and simultaneous stress relief in the four middle sections are carried out.

4.2. The theory of constitutive model and mechanical criterion

The ore and rock of deep deposit in Fankou Lead-Zinc Mine are brittle hard rocks, and the rheological problem of rocks can be ignored. In general, the hard rock is in elastic state at low stress, but stress concentration is generated around the goaf by the excavation, The part of ore and rock can also enter into the plastic state, so the three-dimensional elastic-plastic model is used in the calculation model, and the plastic yield condition is Dracker-Prager criterion (Kwasniewski and Wang, 1999).

$$F = \alpha J_1 + \sqrt{J_2} - k = 0 \tag{1}$$

Where $J_1 = \sigma_{ii} = \sigma_x + \sigma_y + \sigma_z$;

$$J_2 = (S_x^2 + S_y^2 + S_z^2)\frac{1}{2} + S_{xy}^2 + S_{yz}^2 + S_{zx}^2;$$

$$S_x = \sigma_x - \sigma_m, S_y = \sigma_y - \sigma_m, S_z = \sigma_z - \sigma_S;$$

$$S_{xy} = \tau_{xy}, S_{yz} = \tau_{yz}, S_{zx} = \tau_{zx};$$

$$\sigma_m = (\sigma_x + \sigma_y + \sigma_z)\frac{1}{3}$$

$$\alpha = \frac{2\sin\phi}{\sqrt{3}(3+\sin\phi)}$$

$$k = \frac{6c\cos\phi}{\sqrt{3}(3+\sin\phi)}$$

c : Cohesion

ϕ : Internal friction angle

4.3. The scope of calculation model

The scope of mining in middle section of deep orebody is between 550 m and 700 m below ground level, and the horizontal scope of mining is between S3 and-N12; According to the principle of solid mechanics, the influence scope of excavation disturbance is generally 3-5 times of the excavation adit diameter. So, the scope of calculation model is: X= 1662m (the direction of vertical orebody). Y= 1432m (Vertical direction +132m～-1300m), Z= 2800 m (along the direction of the orebody).

4.4. Mechanical parameters of model media

According to the geological characteristics and engineering characteristics of the deep deposit of Fankou Pb-Zn mine, four kinds of mechanical media, namely limestone, lead-zinc ore, cemented backfill and tailings backfill, were considered after the classification and treatment. The determination of mechanical parameters of rock mass was based on the mechanical parameters of rock mass specimen, and according to their rock mass structural characteristics and rock mass classification index. After the comprehensive selection of engineering treatment, the filling physical parameters were also comprehensively selected after engineering treatment, as shown in Table 1.

Table 1. Mechanical parameters of model media

Media	Elastic Modulus (Mpa)	Poisson ratio	Residual strength (Mpa)	Internal friction angle (°)	Tensile Strength (Mpa)	Specific gravity (MN.m^{-3})
Lead-zinc Ore body	21876	0.25	2.0	44	2.1	0.04
Limestone	14495	0.26	2.1	36	1.6	0.0274
Cemented filling body	1480	0.28	1.4	30	0.5	0.023
Tailings filling body	300	0.3	0.03	26	0.01	0.0137

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5. ANALYSIS OF NUMERICAL SIMULATION RESULTS

5.1. Numerical simulation results of stress relief within panel area

The numerical simulation of stress relief within the panel in middle section at 700m below ground level is carried out. The variation of maximum principal stress and minimum principal stress of the stope before and after stress relief within the panel are shown in table 2. And the maximum principal stress contour map of each scheme is shown in Figs. 1-5.

Table 2. The variation of maximum principal stress and minimum principal stress in stope before and after stress relief within panel

Scheme number	Before stress relief		After stress relief	
	Maximum principal stress (Mpa)	Minimum principal stress (Mpa)	Maximum principal stress (Mpa)	Minimum principal stress (Mpa)
M1	32.358	21.05	29.833	21.652
M2	32.481	21.041	28.182	14.978
M3	32.585	21.047	28.315	14.984
M4	32.677	21.055	32.677	14.983

Where M representing scheme 1, 2, 3, and 4, respectively.

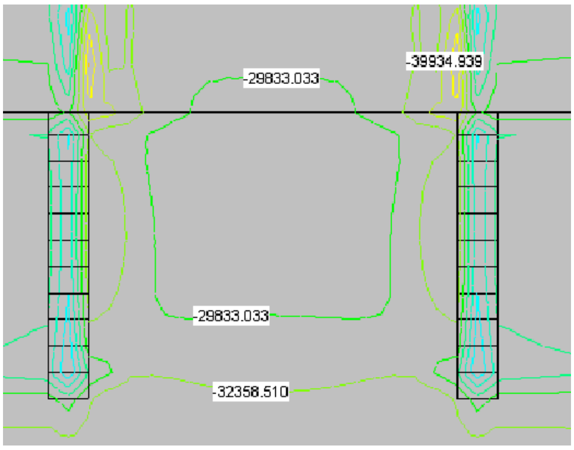

Fig 1. Maximum principal stress contour map of scheme M1

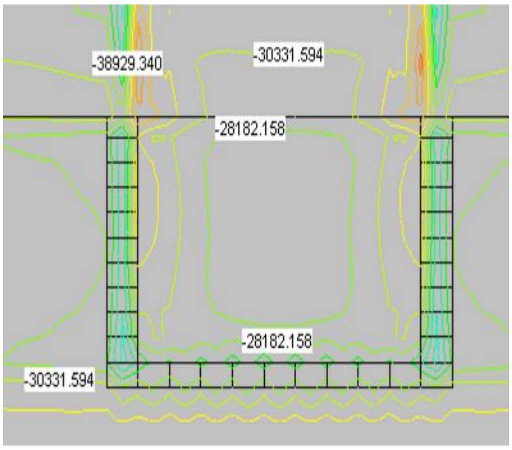

Fig 2. Maximum principal stress contour map of scheme M2

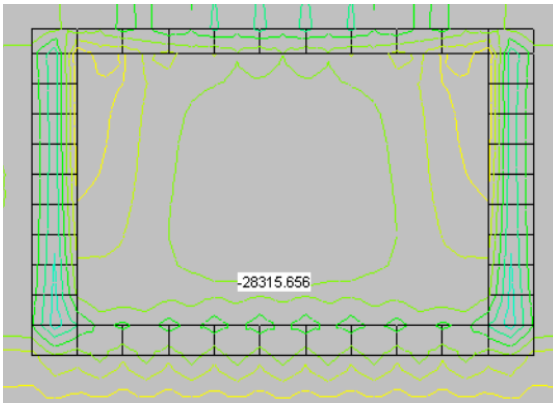

Fig 3. Maximum principal stress contour map of scheme M3

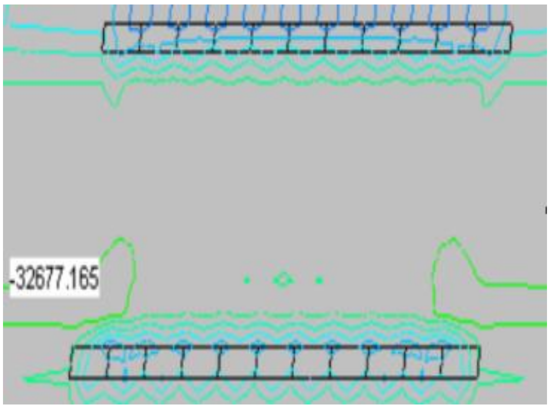

Fig 4. Maximum principal stress contour map of scheme M4

From the above figures, it can be seen that after the stress relief mining of stope at the both ends of the panel (scheme 1, scheme 2 and scheme 3), the maximum principal stress reduction circle has been formed within the panel, and the maximum principal stress is reduced effectively, but the stress relief measures of bottom drawing or roof cutting are only adopted in scheme 4, while the maximum principal stress inside and outside the panel remains unchanged**,** but the minimum principal stress decreases because the bottom drawing or roof cutting only cuts off the vertical stress transfer. Therefore, scheme 4 cannot effectively relieve the stress here.

From the analysis of schemes 2 and 3, it can be seen that the size and scope of the maximum principal stress and minimum principal stress reduction circle in the panel have not changed significantly after including the roof cutting stress relief measure. Therefore, including the roof cutting stress relief measure will greatly increase the cost of stress relief measures. Scheme 2 only changes the sequence of operations on the basis of Scheme 1. Before stope mining in the first or second steps within the panel, bottom drawing is carried out to cut off the transmission of vertical stress and reduce the minimum principal stress value. Therefore, scheme 2 is an ideal stress relief scheme.

5.2. Simulation calculation results of simultaneous stress relief mining in multi-middle sections.

After stress relief mining of stope in the single middle section at 700m below the ground level, a stress reduction zone is formed within the panel, and the stress reduction circles are isolated from each other with a smaller scope; the maximum principal stress is decreased from - 34.217 Mpa to - 30.408 Mpa as shown in Fig 5.

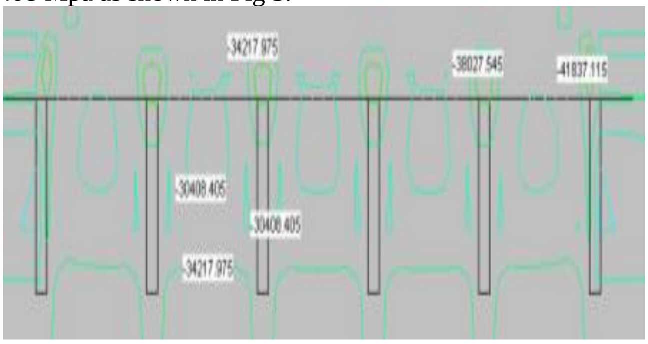

Fig 5. Contour map of maximum principal stress after stress relief in single middle section at 700m below ground level

The two middle sections at 700m and 650m below the ground level are relieved simultaneously, and a large stress reduction circle is formed along the strike panel interval, and the maximum principal stress decreased from -34.217mpa to -30.408mpa, as shown in Fig. 6.

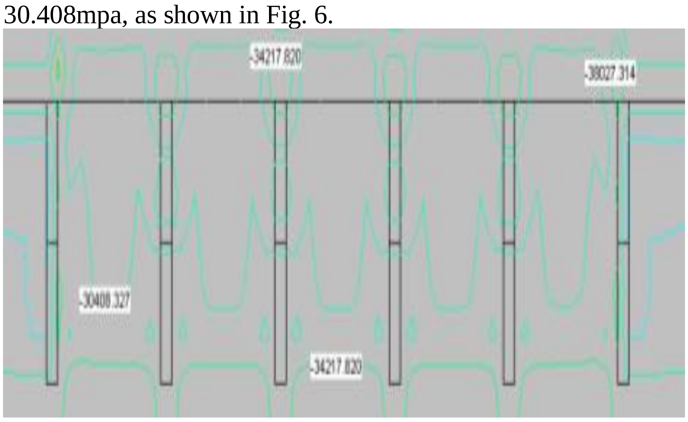

Fig 6. Contour map of maximum principal stress after simultaneous stress relief in two middle sections at 700m and 650m below the ground level

The simultaneous stress relief in three middle sections at 700m, 650m and 600m below the ground level, and the simultaneous stress relief in four middle sections of 700m, 650m, 600m and 550m below the ground level cannot continue to increase the scope of the stress reduction circle, but form mutual and isolated stress reduction circles in the third and fourth middle sections.

From the above analysis, it can be seen that the double simultaneous stress relief measures should be adopted in the middle section of the panel.

6. CONCLUSION

The results of numerical simulation show that, when mining in deep high stress zone of Fankou Lead-Zinc Mine, the high stress in the mining area can be transferred to the surrounding area through the measures of panel stress relief and middle section stress relief, which can reduce the stress in the mining area, improve the stress distribution of rock mass, and control the stress concentration caused by repeated mining, so as to realize safe mining.

In order to effectively reduce the maximum principal stress and minimum principal stress in the panel, it is advisable to adopt stress relief measures of stopes on both sides of the panel and earlier bottom drawing measures for stopes within the panel. In order to improve the stress distribution of rock mass in the whole mining area, the measures of double simultaneous stress relief in the middle section should be taken.

Mining in deep high stress zone is the inevitable trend of future development. The stress relief measures and analysis methods adopted in this paper for preventing rockburst have certain reference value for deep deposits mining and ground stress control in other metal mines.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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