Optimization Study of Stope Structural Parameters in High Stress Zone of Deep Deposit

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Abstract: Mineral deposits are very important valuable materials strengthening the economic development of a nation. The unlimited needs of human being from mineral deposits are leading to the continuous increase in depth of underground mines. Due to the high concentration of ground stress resulting from exploitation of deep mineral deposits, the subsequent frequency of ground pressure hazards is consequently highly increasing, and have strongly hindered the safe and efficient mining. This increased the need for effective underground mine planning and optimization techniques. Adopting rational stope structural parameters is an important measure to realize safe and efficient mining of deep mineral deposits and to control ground pressure hazards. By using large scale nonlinear 3D finite element program, the optimization study of stope structure of deep ore deposit at FanKou Lead-Zinc Mine was carried out through the method of static and dynamic numerical simulation experimental test. The rational stope structural parameters of deep ore deposit exploitation at FanKou Lead-Zinc Mine is recommended to the similar mines elsewhere.

Keywords: High stress zone, Stope structure, Optimization, Ground pressure hazards, Nonlinear 3D finite element.

1.Introduction

As previously, obviously and intensively researched, the unlimited needs of human being from mineral deposits are leading to the continuous increase in depth of underground mines in china and some rest of the world. In China, some metal mines, such as the Hongtoushan copper mine, the Dongguashan copper mine, the Jiapigou gold mine, the Sanshandao gold mine, the Fankou lead-zinc mine, the Linglong gold mine, and so forth, have already reached the depth of 1000 m [1]. The depth of underground mine increases in close association with the increase of ground stress. With this deep deposit exploitation and high concentration of ground stress, the subsequent frequency of ground pressure hazards (rock bursts occurrence) are consequently highly increasing, and have strongly hindered the safe and efficient mining operation [2-5]. According to the complexity of underground mining operation and its mechanical characteristics during operation, it is not easy to completely find the accurate solution of the threats of underground mining. Therefore, it is essential to search for the new manners to deal with the problem existing in underground mining operation. Currently, optimization technique / numerical analysis is adopted to a great extent in mining engineering [6]. Since early 1960's, the optimization techniques had been adopted in mining to improve the safety and efficiency [7]. The determination of the rational structural parameters of stop plays great role for safe exploitation of deep deposit, which then results in high efficiency [6]. The optimization is able to positively increase the value of exploitation process of mineral deposits in terms of assuring optimal results [8].

According to [9], In addition to the stability of mined out area, the stope structural parameters go hand in hand with the efficiency of mining. As long as the deep deposits exploitation probably involves the different technical problems, therefore the advances in technologies applied to determine underground mine plan layout and scheduling should promise underground mining to be optimized [10]. Therefore, by adopting the optimization of stope structural parameters, the safe and efficient mining can be assuredly realized [11].

1.1 Previous optimization studies

Previous studies were conducted on the stope optimization in different ways to improve the safety and efficiency of mining in high stress zone of deep deposits.

In the study of [11], Based on engineering geological investigation of field, Indoor rock mechanics experimental test, and mechanical parameter analysis of macro rock mass, the three dimension calculation model of gently inclined and extremely thin orebody of Guihua copper mine was established by the three dimension finite element computer based program, and the 9 schemes were suggested for computational analysis of structural parameters of stope optimization 3D −σ. Throughout the numerical computation of span and pillar width of the stope, the reasonable structural parameters of stope were achieved. Therefore, safety and efficiency enhanced.

From the research conducted on the optimization of structural parameters for mining large iron ore stope by filling method, [12] went through a serialized 3D simulation and analysed the relationship between the safety of deposits exploitation, Parameters of rock displacement and parameters' design. From this simulation and analysis, the structural parameters of stope were optimised.

Li and Li [13] conducted a study by using the three dimensional-sigma numerical simulation method to study a stability of the surrounding rocks in dissimilar structural parameters of stope, and then rational dimensions of room and pillar for phosphorite mine were designed.

In the study conducted by [14], Due to the high intended level of daily production and serious ground stress, strong ground hazards tendency in exploitation of Sanshandao deep gold mine, 3 exploitation techniques have been discussed in three corners such as economic, technical and safety. On the basis of exploitation indexes quantification and fuzzy analysis of exploitation indexes, a fuzzy optimization model has been constructed to choose the optimal exploitation technique. The results revealed that the exploitation technique by alternating room and pillar with upward backfilling is an assured optimal technique to realize safe exploitation linked to high productivity in Sanshandao deep gold mine.

In the subsequent study of [15], the room and pillar widths varied from 6m to 15m. For enhancing the productivity and control the ground hazards from deep deposit exploitation of Sanshandao gold mine, a fuzzy optimization model with eleven evaluation indexes is constructed to select the optimal structural parameters from 8m×8m, 8m×10m, 10m×10m, 10m×12m and 12m×12m. The results revealed that structural parameter of optimal stope to realize safe exploitation linked to high productivity was 10m×10m. From the above literatures, it is found that the optimization is able to positively increase the value of exploitation process of mineral deposits in terms of assuring optimal results [8].

2.Overview on Fankou Lead-Zinc Mine

Among the mines stated in the first paragraph of introduction, Fankou Lead-Zinc Mine is the study area in this paper. It is located in Renhua county, Guangdong province, China, as shown below on the Fig.1.

Figure 1. Location of study area (Fankou Lead-Zinc Mine) in Renhua county, Guangdong province, China

China is the second ranked in the world's countries with and produce abundant Lead-Zinc resources with high reserves [16]. Fankou Lead-Zinc Mine is the main production base of lead-zinc concentrate in China, its lead-zinc concentrate output accounts for about 10% of the national lead-zinc concentrate output. it is one of the few hard rock metal mines with a proven depth around 1000m in China. This mine has already initiated deep mining.

Because of deep rock mass is in high ground stress, high temperature, high permeable pressure environment and has strong time effect, the structure, basic behavior characteristics and engineering response of deep rock mass are fundamentally changed due to the frequent and sudden occurrence of serious ground pressure hazards in deep mining. This requires a thorough study on the prevention and control of ground pressure hazards in deep mining. Adopting rational mining layout and optimized stope structure is very important, because it is one of the most fundamental and effective measures to prevent and control ground pressure hazards [17]. In this paper, the method of dynamic and static numerical simulation experiment test was adopted by using the large nonlinear 3D finite element numerical computational program. The optimization study of stope structural parameters of deep deposit at FanKou Lead-Zinc Mine was carried out with a view to provide decision-making basis for deep ore deposit exploitation and ground pressure control in this field.

3. The occurrence characteristics of deep deposit

Fankou lead-zinc ore deposit was proved to be one of the china's largest ore deposits [18]. Genesis of Fankou Pb-Zn deposit is stratabound lead-zinc deposit of sedimentary reformed pyrite type. In general, the ore body is big in the middle and small at the top and bottom. The deep deposits are between -360m and -750 m levels, and the Shiling orebodies and Shiling South orebodies are between 207 and 218 lines. The deep orebodies in Shiling are mainly located in the footwall of F3 fault. The proven reserves of the main orebodies Sh209 and Sh2l4 account for 76.9% of the deep proven reserves. The strike length of ore body ranges in 1000-1350m.

With the increase of mining depth (According to estimation of measured geothermal gradient, the deep rock temperature at level of -750 m will reach 42℃), the temperature of the surroundings will rise. In the deep deposit, there are Lead-Zinc ore which contains high sulfur content and some single pyrite. The ore is oxidable, easy to agglomerate, liable to heat generation or liable to spontaneous combustion. The original rock stress is primarily tectonic stress. According to actual measurement, the maximum principal stress (σ_1) at level of -650m is 31.2Mpa and it approximates to horizontal direction. The ratio of the maximum principal stress and vertical stress is between 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 and deep development observation, it is shown that deep ore deposit and rock mass have the tendency of medium rock burst.

4. Static and dynamic finite element analysis model

Static finite element analysis, the tectonic stress field variable Φ as [19]:

$$\Phi^{(e)}(x,y,z)=[N]\cdot[\Phi]^e=\sum_{i=1}^{n}Ni(x,y,z)\Phi i \tag{1}$$

Where: shape function and the stress field variables in the space are both the location coordinates (z, y, z) function, cell node parameters Φi does not change over time, is a question of the constant demand. This finite element matrix derived the form of the equation:

$$[K]\cdot[\Phi]=[F] \tag{2}$$

Where [K] is the total stiffness matrix; [F] is the summation point load sequence matrix; [Φ] the total node parameter matrix. In order to sum up the parameter matrix of the point, the node displacement in the stress field analysis is [Δ]. However, in dynamic finite element analysis, the field variable Φ should be constructed into the following two forms [20]：

$$\Phi^{(e)}(x,y,z,t)=[N]\cdot[\Phi]^e=\sum_{i=1}^{n}Ni(x,y,z)\Phi i(t) \tag{3}$$

$$\Phi^{(e)}(x,y,z,t)=[N]\cdot[\Phi]^e=\sum_{i=1}^{n}Ni(x,y,z,t)\Phi i \tag{4}$$

In the finite element model shown in equation (3), only the spatial domain is discretized, and the problem of an instantaneous t is taken into account, It is also assumed that in this instantaneous and steady state analysis, the shape function N_i is the usual shape function, while the $\Phi i\ (t)$ is the summation point parameter array matrix which changes with time, and the node displacement [Δ] in the analysis of stress field. In the other finite element model shown in equation (4), the problem is regarded as a time-varying problem in a four-dimensional space-time domain. In this case, the shape function Ni includes space and time, that is to say, the whole region of space and time is discrete.

According to the above modeling idea, after the structure is discretized, the dynamic equilibrium equation of each node in the motion state is as follows:

$$\{Fi\}+\{Fd\}+\{Fs\}=\{p(t)\} \tag{5}$$

In the left side of Eq.5 followed by the inertial force $\{Fi\}$, the damping force $\{Fd\}$ and flexible (elastic)force $\{Fs\}$ are all vectors; the right side is the dynamic (power) load vector $\{p(t)\}$ .that is to say the dynamic equation of the system is established as follows:

$$M\Delta''(t)+C\Delta'(t)+K\Delta(t)=Q(t) \tag{6}$$

Where Δ"(t) and Δ'(t) are the node acceleration vector and node velocity vector of the structure respectively, M, C, K and Q (t) are the system mass matrix, damping matrix, stiffness matrix, and node load vector respectively from their matrix and vector integration unit [21].

In this study, static finite element and dynamic finite element simulation method was adopted to optimize stope structure parameters in deep ore deposit mining. Firstly, according to the rock mass physical and mechanical properties and characteristics of in-situ stress of deep deposit at Fankou Pb-Zn mine [22], the elastic-plastic theoretical calculation model was constructed, and the static finite element numerical simulation analysis of the structure parameters of different stopes in deep ore deposit mining was carried out. Then on this basis, the dynamic finite element method is used to optimize.

5. Simulation calculation under static load

5.1 Calculation models and scenarios

According to the experience of upper mining in Fankou Lead-Zinc Mine and the characteristics of mechanized upward slice and fill mining method in deep orebody panel area, four kinds of deep stope width were selected as 6m, 8m, 10m and 12m, and three kinds of slice height were selected as 4m, 5m and 6m. 10 models were established. The models are briefly described in Table1. The mining steps of simulation calculation were divided into nine steps [23].

Table1. Static model stope size

Model Number	Stope width (m)	Slice height (m)
M1	6	4
M2	6	5
M3	8	4
M4	8	5
M5	8	6
M6	10	4
M7	10	5
M8	10	6
M9	12	4
M10	12	5

Range of calculation model, X = 560m (perpendicular to the direction of ore), Y = -400m - -850m (a total of 450m), Z = 660m~732m (along the ore body strike). Considering the deep characteristics of Fankou Pb-Zn deposit, the stress of the rock mass was mainly tectonic stress. The lateral pressure coefficient of the model was 1.05 in X direction and 1.5 in Z direction. The elastoplastic model was used in the computational model, and the plastic yield condition is Dracker-Prager criterion [24].

5.2. 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, refer to table 2.

Table 2. Mechanical parameters of model media

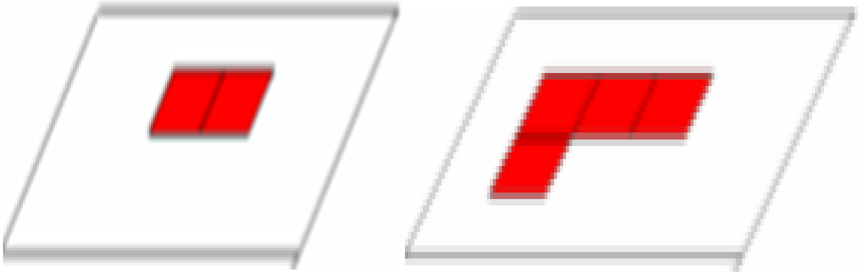
kinds of mechanical medium	Modulus of elasticity（Mpa）	Poisson ratio	Residual strength (Mpa)	Internal friction angle（°）	Tensile Strength（Mpa）	Specific gravity（MN/ m^3）
Lead-zinc Ore body	21876	0.25	2.0	44	2.1	0.04
Limestone	14495	0.26	2.1	36	1.6	0.0274
Cemented filling body	1480	0.28	1.4	30	0.5	0.023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

5.3. Calculation of results and analysis

Based on the model calculation results of 10 stopes structural parameters, the minimum principal stress σ_3, maximum principal stress σ_1, factor of safety and plastic failure zone of the surrounding rock, roof of stope, backfilling unit, hanging and foot wall rock in the stope were analyzed, and the results are shown below.

(1). Because of the large tectonic stress field in deep orebody, the roof of the first stope in the pan area bore large tensile stress and compressive stress. The maximum tensile stress was 11.62~15.67 Mpa (located in the center of the stope roof), and the maximum compressive stress was 66.35~78.57 Mpa (located on both sides of the stope roof). During room mining, the roof of the stope may collapse due to tensile failure, and local caving (subsidence) may occur; while mining the pillar of stope is under the pressure-free arch, the maximum tensile stress (located in the center of the stope roof) and the maximum compressive stress (Located at the footwall of stope roof) are all reduced because when mining room of stope, the pillar bears a larger load which leads to a high compressive stress, and plastic deformation. Due to this high compressive stress and plastic deformation, the damage scope of the roof of pillar stope is larger than that of one-step stope, so effective support should be carried out on time to ensure the effective and safety of mining operation.

(2) With the increase of slice height, the failure location of stope not only occurs in the roof, but also in the upper and middle parts of the two states of stope, and the plastic failure zone of the two states of stope tends to increase. Fig. 1 is a sketch map of plastic failure zones in two states of stope when the width of stope was 8m and the height of slice is 5m and 6m respectively, and when the roof height was 9m and 10m respectively after the fifth slice mining, the shadows in the figure are plastic failure zones. When the slice height was 4 m, there was no plastic failure zone in the two states of the stope. Therefore, the slice height should not exceed 5 m.



a **b**

Figure 1. Variation of plastic failure zone of two states in stope with slice height
a) Slice height of 5M (Goaf- roof height of 9M) **b**) Slice height of 6M (Goaf- roof height of 10M)

(3) With the increase of stope width, the maximum compressive stress (located on both sides of stope roof) in one step stope has the tendency of decreasing, the maximum compressive stress (at the place where the roof of the stope is located next to the footwall) of the two step pillar stope has the tendency to increase. Fig 2 shows the change of maximum compressive stress of stope roof with stope width when the third stope was 5m of the slice height. With the general comprehensive consideration of room and pillar, the width of stope should be 8~10m.

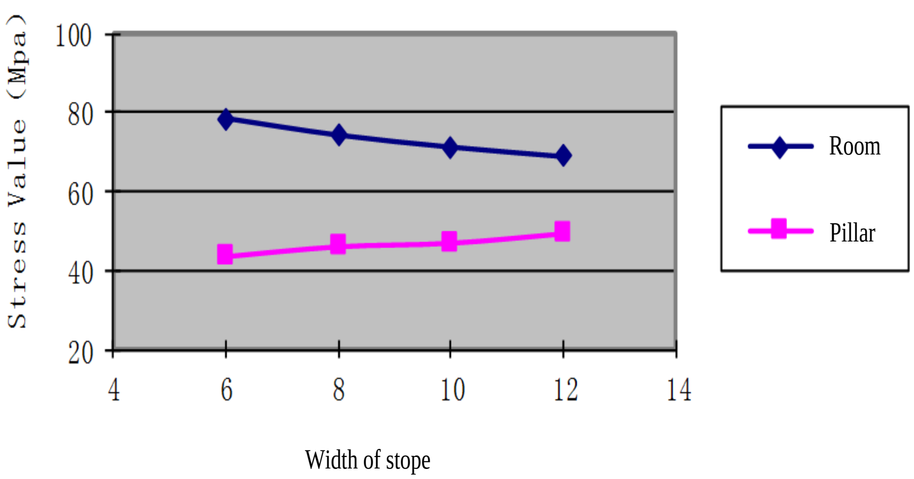
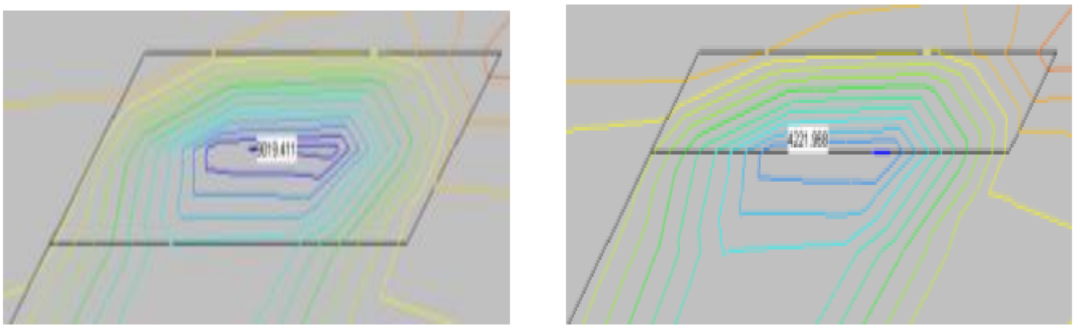


Figure 2. Change of maximum compressive stress trend of roof with stope width when the third stope was 5m of the slice height.

(4) Cemented backfilling has little effect on the stress extremum of the roof of the goaf, but cemented backfilling can significantly improve the stress distribution of the two states, reduce the magnitude and scope of tensile stress and the upward extension height. Fig.3 shows that when the width of stope was 10m and the slicing height was 4m, the maximum tensile stress of the two states after stope filling decreased from 9.02 Mpa to 4.22 Mpa. Therefore, the goaf should be filled in time to increase the filling density.



a **b**

Figure 3. Tensile stress variation in two states of stope before and after stope filling;
a) Before filling σ3 = -9.02 Mpa **b**) After filling σ3 = -4.22 Mpa

6. Simulation calculation under dynamic loads

Rock burst and the high ground temperature are serious problems in deep mining of Fankou Lead-Zinc Mine. According to the preliminary studies, the deep ore and rock have the tendency of medium to strong rock burst, and according to the estimated geothermal gradient, the rock temperature at level of -750 m will reach about 42°C. According to some abroad observation and research results, showed that the rock burst and ground temperature have the characteristics of progressive development to the deep. Therefore, on the basis of static finite element simulation, it is necessary to use dynamic finite element method to optimize the stope structure parameters.

6.1. Mechanical model and parameter selection

According to the characteristics of the 3D-σ finite element software, the temperature difference between the original temperature layer and the excavation face and the dynamic load acceleration are taken as the dynamic finite element calculation parameters. Therefore, the average temperature difference between the original temperature layer and the excavation face was 5°C, and the linear expansion coefficient of the ore and rock was 8×10^{-6}. According to the research results of rock burst in Changsha Institute of Mining Research, rock burst was regarded as microseismic action, and the acceleration of rock burst was 0.01g. The direction of rock burst action was parallel to the direction of maximum principal stress. Based on the results of static finite element calculation, four models are established by selecting the stope width of 8m, 10m and the slice height of 4m and 5m, as shown in table 3.

Table 3. Dimension of stope structure based on dynamic model

Model Number	M11	M12	M13	M14
Stope width (m)	8	8	10	10
Slice height (m)	4	5	4	5

6.2. Analysis of calculation results

After the third step of mining, the stress and other changes of the roof of the first mining room and stope are shown in Table 4.

Table 4. Stress and other states of roof in stope of first room mining after the third step mining

Model No.	Minimum principal stress （Mpa）		Maximum principal stress （Mpa）		Factor of safety		Relaxation coefficient		Vertical displacement (MM)
	Max. value	Min. value	Max. value	Min. value	Min. value	Max. value	Min. value	Max. value	
M11	-22.05	13.79	-78.66	-38.84	0.38	2.61	-1.16	0.87	26
M12	-21.99	14.06	-78.50	-37.89	0.54	2.63	-1.31	0.79	25
M13	-21.88	14.62	-75.61	-31.97	0.41	2.65	-1.25	0.914	28
M14	-22.14	13.37	-75.25	-38.04	0.3	2.57	-1.24	0.86	28

Through the analysis of the results of static and dynamic finite element numerical simulation, it is found that:

(1) Under the action of dynamic load, the maximum principal stress of stope roof increased significantly by 15% ~16%, while the minimum principal stress did not change significantly. This is mainly due to the assumption that the seismic force acts in the direction of the maximum principal stress. When temperature

difference (5°C) was taken into account, the change of roof stress was not obvious. So, the attention should be paid to measure the actual temperature difference in future production.

(2) Under the action of dynamic load, the safety ratio of roof of stope generally decreased and the plastic failure area increased.

(3) Among the four dynamic models, M11 model (stope width 8M, slice height 4M) had lower maximum principal stress, smaller displacement of surrounding rock, and narrow distribution of plastic failure zone, which was a relatively optimal scheme.

7. Conclusion

Through the numerical simulation of stope structural parameters of deep deposit under dynamic and static load in Fankou Lead-Zinc Mine, the following conclusions are drawn:

(1) In the deep deposit mining of Fankou Lead-Zinc Mine, it is reasonable to adopt the panel mechanized upward high slicing and backfilling mining method, so, the mining operation is safe.

(2) The stope structure parameters for exploitation of deep deposit should be: 8m width of stope and 4m height of slice. At this point, the principal stress around the stope is at a lower level, the displacement of surrounding rock is small, and the distribution of plastic failure zone is narrow, which is a better scheme.

(3) Cemented backfilling has little effect on the stress extremum of the roof of the goaf; however, cemented backfilling can significantly improve the stress distribution of the two states, reduce the magnitude and scope of tensile stress and the upward extension height, therefore, the goaf should be backfilled in time to increase the filling density.

(4) Local collapse may occur in the stope during the mining; There may also be an increase in the collapse area during a two-step back to the mining of pillars. Therefore, effective support should be carried out on time to ensure the safe mining operation.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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