Research Article

Improving the Stability of Subsurface Structures in Deep Metal Mines by Stress and Energy Adjustment: A Case Study

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1. Introduction

The excavation depth for metal mines worldwide has reached $\sim$1000 m to $\sim$2000 m, and the maximum mining depth is over $\sim$4000 m [1]. The in-situ stress for deep mines is normally high, which results in more and more mining/excavation-induced hazards, including rockburst, roof collapses, and shaft failure. It is well known that the excavation activities change the stress field of rock and the mining method, excavation order, and support time have effects on the stress change [2]. Therefore, some theoretical methods and practical technologies are proposed and developed to adjust the stress and energy in targeted areas, which improves the stability of rock mass in deep mines [3].
fault. Therefore, a reasonable engineering layout is very helpful for reducing the risk of mining-induced risk. Feng et al. [12] summarized several methods to reduce the risk of rockburst, such as optimization of the excavation (or mining) size and sequences, high-stress aided blasting, boreholes to release energy, and advanced support system with the capacity of absorbing energy. Moreover, the support method, time, and sequence could also affect the stability of deep rock mass. The deformation and failure of rock are affected by many factors, but the dominant factors are stress level and energy evolution. Therefore, it is of significance to adjust stress and energy for deep mining. This study is focused on employing some advanced engineering methods and practical management strategies for adjusting stress and energy in deep gold mines located in Jiaodong, China. First, key factors resulting in mining hazards and the control strategy are analyzed and discussed. The geological structures, failure characteristics of deep rock, and in situ stress field in the Jiaodong Peninsula are analyzed, observed, and measured. To reduce the risk of deep mining hazards, the engineering applications of stress transferring by mining optimizations, pressure relief by boreholes, and energy release by optimizations of excavation and support are studied by site monitoring and numerical simulations.

2. Deep Mining Hazard and Its Control Strategy

After the ore body has been excavated in deep hard-rock mines, the original stress balance is destroyed. The stress in the surrounding rock of subsurface structures is redistributed, and it reaches a new balance. Different zones, including concentration, release, and transformation of stress, are generated inside the surrounding rock. As a result, stress changes from three-dimensional to two-dimensional, making surrounding rock bear tensile stress. Once the stress exceeds the tensile strength or the compressive strength of rock mass, it causes joints and cracks to open or close [17, 18], leading to subsidence of stope roof, wedge caving, bottom swelling, spalling, slip, and even rockburst. All these phenomena are collectively known as ground behaviors caused by high stress [19].

The above analysis indicates that ground failures and instability are mainly affected by stress level, the structural plane of rock mass, and the mechanical properties of rock mass itself. High in-situ stress, especially tectonic stress, is necessary for rockburst [20], which is also the source of ground pressure in stopes and tunnels. In underground mines, many failures and instabilities could be attributed to the mechanical properties and the stress state of the rock mass, which is manifested as the contradiction between strength and stress:

\[ K\sigma_v > S_c, \]

(1)

where \( K \) is the stress concentration factor; \( \sigma_v \) is the vertical component of original rock stress, MPa; and \( S_c \) is the rock strength, MPa.

Considering the effect of structure on rock strength, the above formula can be written as follows:

\[ K\sigma_v > K_s S_c, \]

(2)

where \( K_s \) is the structure weakening factor.

From formula (1) and formula (2), it is noted that instability occurs when the stress level in rock mass exceeds its strength, especially along the structural plane.

Due to the difference in ore body shape, excavation (or mining) sequence, and mining methods, stress control becomes complicated in deep metal mines. The strategy for ground failure control can be summarized into four steps. Firstly, the tunnel’s axis direction should be as parallel as possible to the maximum principal stress direction. The layout of some large subsurface structures such as chambers and shafts should avoid stress concentration areas, especially those areas near faults [21]. Secondly, transfer the secondary stress by optimization of excavation sequence and structure parameter, mining method innovation. Thirdly, pressure relief [22] and energy prereleasing technology are suggested to reduce stress concentration and form an unloaded zone. Finally, the surrounding rock mass can be reinforced by support components. Ground support requires that the support system be strong enough to sustain the momentum of the ejecting rock on the one hand and tough enough on the other hand to absorb the strain energies released from the rock mass [23]. So, it should adopt the flexible support for rock mass reinforcement which has the capacity of deformation and energy dissipation, such as flexible composite support, yield anchor, or cable to deform together with surrounding rock. The flexible support can not only control the stress but also prevent the further development of the structural plane in the rock mass. In summary, a control strategy and technical methods system for ground failure control is proposed in Figure 1.

3. Case Study

3.1. Background. The Jiaodong Peninsula of Shandong Province has many important metallogenic belts, such as the Zhaoyuan-Laizhou, the Qixia-Penglai, and the Muping-Rushan [24] (as shown in Figure 2). The three mainly developed ore-controlling fault zones are the Sanshandao-Cangshang fault (SSDF, see Figure 1), Xincheng-Jiaojia fault (JJF), and Zhaoyuan-Pingdu fault (ZPF). The types of gold deposits are mainly altered rock in fracture zones and quartz veins [25]. The lithology is dominated by a series of altered rocks, including sericite, serialized granite, serialized granitic
High stress

Avoiding

Transferring

Reducing

Supporting

Engineering layout

Secondary stress

Lower stress level

Coordinate deformation and energy absorption

Excavation sequence optimization

Mining method innovation

Structure parameter optimization

Pressure relief

Energy pre-releasing

Flexible composite support

Yield anchor

Yield cable

Figure 1: Strategy and system of technical methods for ground failures control.

Figure 2: Distribution of faults and metallogenic belts in Jiaodong, China [24].
3.1.2. Stress Level. Totally, 109 groups of in-situ stress as shown in Figure 5. exert a large force on support until it was completely failed, the rock mass was broken, the tunnel roof would fall and tunnels were severely deformed after a period of exposure. If as spalling rib and rock ejection, which caused a particular ranging from −71 m to −2300 m. It shows that the maximum horizontal principal stress in each group is more significant than vertical stress. At approximately 2.1 times vertical stress. At −1000 m depth, the maximum principal stress is up to 54.7 MPa.

Therefore, ground failures are mainly caused by high stress combined with a structure plane in northwestern Jiaodong at the current mining depth. The premise of control rock mass failures is to master the stress level and pay attention to the structure plane.

3.2. Stress Transferring. As mining advances, the stope’s scale and shape change frequently, resulting in continuous secondary stress around the stope. The key of the stress transferring method is to transfer the stress of the stope to a nonmining area or surrounding rock.

In a mining area near the SSDF zone, mining depth has entered the −1050 m level, and the maximum horizontal principal stress is over 40 MPa. To ensure rock mass and improved ore production, two kinds of mining methods are designed: (1) the upward horizontal backfill method and (2) the approaching backfill method. A test stope is designed along the ore body strike, with a length of 60 m and a width of 40 m (average ore body thickness). To compare the total stress level of the two methods and the stress transferring process, a numerical simulation model with simulated mining depth ranges from −1050 m to −1005 m is developed in FLAC3D. In this model, the X-axis is perpendicular to the ore body strike, the Y-axis is along the ore body strike, and the Z-axis is along the plumb direction. It has a total of 1,188,000 elements, 1,231,466 nodes, and the 3D size is 240 m × 200 m × 45 m. The ore body has a dip angle of 40°, a fault called F1 is close to and almost parallel to the ore body, which is located in the hanging wall of the ore body, only about 40 cm thick, as shown in Figure 7. Physical and mechanical parameters for numerical simulation are shown in Table 1.

Table 2 shows two excavation schemes for optimizing the stress transferring effect [31]. The stress fields for the two exaction schemes are obtained by numerical simulations. In Scheme 1, as shown in Figure 8, if the stope is not filled, an unloading zone at the upper of the stope is formed after the excavation by Steps 1–3, and the reduction value of maximum stress about 7 MPa. However, the surrounding ore body’s stress in two sides increases from 23.36 MPa to 25.59 MPa (Step 2), then reduced to the original level (Step 3). It can also be seen that a stress concentration zone is formed in the vault of stope in Step 1 and Step 2. Therefore, the stress reduction by excavation alone is limited. However, after backfilling without the roof contacted, the stress level in the backfill and the roof is reduced. The maximum principal stress is less than 2 MPa (Step 4), but the stress in the surrounding ore body is still high.

In Scheme 2, as shown in Figure 9, the roof and pillar stress has a slight reduction and the stress change in the surrounding ore body is not apparent in Step 1 and Step 2. After the first backfilling with the roof contacted (Step 3), an unloading zone is formed around the stope and it can also help reduce the stress in the pillars. In the subsequent excavation process, the stress around the stope and the filling body reduces to less than 2 MPa, and the stress value of the surrounding ore body also decreases to about 14.0 MPa (Step 4). After the final backfilling with the roof contacted,
Figure 3: Roadways with developed joints and fractures. (a) ~1005m level, located at SSDF zone. (b) ~815 m level, located at JJF zone.

Figure 4: Rock core disking phenomenon in an exploration hole with depth 2017 m.

Figure 5: Continued.
the stress of the filling body is about 1 MPa. The stress of the surrounding ore body is significantly reduced.

Therefore, a better stress transferring effect can be obtained by Scheme 2, which not only can reduce the stress around the stope and filling body but also reduce the stress in the surrounding ore body. Scheme 2 can improve the stability of rock during mining and benefit the excavation of the adjacent stope.

3.3. Pressure Relief by Boreholes. During mining and tunnel construction, pressure relief holes can be drilled and blasted...
in two sides or roof of the tunnel and stope to release the secondary stress caused by mining. A sublevel open stoping with subsequent backfill method is designed in −780 m level of a large gold mine located at SSDF zone, and a stope is chosen as industrial test stope. Before mining, a row of pressure relief holes is constructed in the adjacent drilling tunnel. The hole diameter is designed to be 65 mm, the bottom spacing between the two holes is 0.4 m, with a depth of 12 m. After the pressure relief holes are blasted, the area to be mined would be separated from adjacent areas by a connected cutting seam, which will help cut the mining disturbance stress transmission and form a local lower pressure zone.

As shown in Figure 10, an industrial stope is divided into three sections along strike: the south section, the middle section, and the north section. To compare stress-relief effect, different stress-relief measures are adopted in these three sections. The south section is to be mined without stress releasing holes. Stress-relief holes and presplit blasting are arranged in the middle section. Only pressure relief holes

| Location  | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | Poisson’s ratio | Cohesion (MPa) | Interfriction angle (°) | Compressive strength (MPa) | Tensile strength (MPa) |
|-----------|----------------|-------------------|--------------------|----------------|----------------|------------------------|---------------------------|-----------------------|
| Hanging wall | 2706           | 3.37              | 2.8                | 0.21           | 11.4           | 31.3                   | 48.2                      | 4.37                  |
| Football  | 2635           | 5.48              | 3.45               | 0.24           | 42.8           | 36.9                   | 60.1                      | 5.98                  |
| Fault     | 1925           | 0.595             | 0.378              | 0.26           | 0.128          | 18.4                   | 20.6                      | 0.0198                |
| Ore body  | 2710           | 2.51              | 1.35               | 0.19           | 21.5           | 33.1                   | 57.6                      | 3.44                  |
| Filling body | 1610         | 0.304             | 0.0245             | 0.17           | 0.261          | 35.6                   | 7.43                      | 0.212                 |

**Table 2:** Designed mining schemes of test stope.

| Mining method | Simulated mining scheme | Stress boundary |
|---------------|-------------------------|-----------------|
| Scheme 1: the upward horizontal backfill method | Step 1: excavating an undercut roadway of 4 m × 4.5 m in the middle of a stope | Initial Szz −26.6 MPa |
|               | Step 2: excavating north of stope | Initial Sxx −43.6 MPa |
|               | Step 3: excavating south of stope | Initial Syy −26 MPa |
|               | Step 4: backfilling height of 3 m with the roof uncontacted |                       |
| Scheme 2: the approaching backfill method | Step 1: excavating 4 approaching roads in the stope from the middle to the north | Initial Szz −26.6 MPa |
|               | Step 2: excavating 3 approaching roads in the south of stope | Initial Sxx −43.6 MPa |
|               | Step 3: backfilling the 7 roads with the roof contacted | Initial Syy −26 MPa |
|               | Step 4: excavating the remained 8 roads |                       |
|               | Step 5: backfilling the 8 roads with the roof contacted |                       |

**Figure 8:** Stress transferring process of Scheme 1 (contour of maximum principal stress, X = 70 m).
are arranged in the north section and whether to conduct presplit blasting to form a cutting seam or not depends on stress relief in the middle section. The drilling process is started from center point A. Boreholes in section A-B are drilled first and those in section A-C are drilled later. To obtain the pressure relief effect of boreholes and blasting, the stress values before and after the drilling and blasting are monitored. Eight borehole stress gauges are arranged in the south, middle, and north sections. The tracking monitoring is carried out for more than two months. The results are shown in Figure 11. The stress values of gauge #1, #2, #3, #6, and #7 are reduced to various degrees and tend to stabilize. Its average reduction is 23.80%, and the maximum reduction reached 37.56%. Nevertheless, there is an apparent increase in gauge #4, #5, and #8 and a followed sharp decline in gauge #5 and #8, due to later disturbance caused by mining activity in the South section. However, compared with the middle and north sections, the middle section’s stress-relief effect is not better than the north section. Consequently, as a whole, it can reduce stress by proper boredrilling to maintain the stability of the stope, but the effect of presplit blasting is limited or need to be optimized.

3.4. Stress-Reducing by Energy Prereleasing. Rock excavation will inevitably lead to a large amount of elastic strain energy accumulated in the stress concentrated area. If energy accumulated in rock exceeds its capacity, instability or rockburst will occur [32]. The energy-releasing in advance technique requires a certain amount of time and space for energy-releasing before permanent shaft or tunnel support.
It is the surrounding rock rather than the permanent support to bear stress.

In a gold mine located at the JJF zone, a new main shaft has a designed diameter of 7.5 m and a net diameter of 6.7 m, with a total depth of 1527 m, from +32.9 m to -1494.1 m. After excavation, the stress in rock mass near-surface is redistributed, and a plastic failure zone would be produced. The tangential stress and radial stress in the plastic failure zone increased with increasing distance from the shaft center. It would increase to a much higher value than the in situ stress at the elastic-plastic interface.

A cross section of -1250 m level was selected as an example, where $P_0 = 38.96$ MPa, $c = 6.55$ MPa, $\varphi = 37.08^\circ$, and $a = 3.75$ m. The stress level and the plastic failure zone can be calculated by theoretical formulas (6)–(8) [33]. The result shows that $\sigma_r = 67.74$ MPa, $\sigma_p = 10.26$ MPa at the elastic-plastic interface, and $R_0 = 4.849$ m. It means the depth of the plastic zone is 1.10 m.  

\[
\sigma_r(p) = (p + c \cot \varphi) \left( \frac{R}{a} \right)^{2 \sin \varphi/(1-\sin \varphi)} - c \cot \varphi, \quad (6)
\]

\[
\sigma_\theta(p) = (p + c \cot \varphi) \left( \frac{R}{a} \right)^{2 \sin \varphi/(1-\sin \varphi)} \left( 1 + \frac{\sin \varphi}{1 - \sin \varphi} \right) - c \cot \varphi, \quad (7)
\]

\[
R_0 = a \left( \frac{1 - \sin \varphi}{p + c \cot \varphi} \right)^{(1-\sin \varphi)/2 \sin \varphi}, \quad (8)
\]

where $\sigma_r(p)$ is the radial stress in the plastic zone, MPa; $\sigma_\theta(p)$ is the tangential stress in the plastic zone, MPa; $c$ is the cohesion, MPa; $\varphi$ is the internal friction angle, $^\circ$; $P_0$ is the supporting reaction force, MPa; $R_0$ is the uniformly distributed in-situ stress, MPa; $a$ is the radius of the shaft, m; $r$ is the distance from the center of the shaft, and $R_0$ is the radius of the plastic zone, m.

Traditional construction process usually installs permanent support too early after a cycle (usually 4 m in China). However, it can be seen from the interaction model between surrounding rock and support, as shown in Figure 12, if we give the temporary support at time $t_0$ and give the permanent support at time $t_1$ (as support deformation characteristic curve 1), supporting material with higher stiffness is required. Besides, the permanent support may be damaged due to the high pressure on the support. If we give the temporary support at time $t_0$ and give the permanent support at time $t_1$ (as support deformation characteristic curve 2) on the premise of maintaining the stability of surrounding rock, it can not only ensure lining safety but also save support costs. Therefore, it is necessary to release energy accumulated in rock mass in advance to control stress effectively.

In this study, a construction section from elevation -930 m to -1271 m of 1527 m deep shaft is selected as the research object. Resin bolts and split set bolts with a particular ability to deform are selected as temporary supporting materials. Metal mesh and bimetal bars are selected to prevent the loose rock from slipping. The main functions of temporary support are to release dilatancy pressure and control loose confining pressure. According to rock mass rating (RMR) and geological strength index (GSI) classification results, the surrounding rock’s stable height can reach 16–20 m without permanent support, as shown in Table 3. Besides, in Canada, a span of surrounding rocks without permanent support is suggested to be 2–3 times shaft diameter, and the corresponding construction time of this

![Figure 11: Stress curves of eight monitoring gauges: (a) vertical stress change curve and (b) horizontal stress change curve.](image)
The energy adjustment time of the new main shaft is determined to be 4 days, and the span of surrounding rock without permanent support immediately was 16 m (4 sinking cycle heights). The construction process can be shown in Figure 13.

To investigate stress change in surrounding rock and lining, a shaft model is established to analyze the maximum stress distribution in surrounding rock and concrete lining after improving the bench height without giving permanent support too early to release the energy in advance. Figure 14 shows that the maximum principal stress in the surrounding rock is reduced to less than 10 MPa in the range of 0–56 m from the working face, and most areas were close to zero. Similar variation patterns can be seen from the stress distribution in the concrete lining. The results show that improved technology can achieve a good stress control effect and create a lower pressure environment for the concrete lining.
4. Conclusions and Discussion

Through comprehensive geological investigation, field measurement, and in situ stress field analysis, the rock failure characteristics for deep gold mines in the Jiaodong area were obtained and adjusting stress and energy of excavated zone were determined as the main methods to improve the stability of subsurface engineering in deep mines. Conclusions can be given as follows:

(1) The maximum horizontal principal stress is the largest principal stress in the Jiaodong area, which indicates that the in situ stress field is dominated by horizontal tectonic movement. At −1000 m depth, the maximum principal stress is over 50 MPa. The ground failures are mainly caused by high stress.

(2) Compared with the open stoping method, the backfill mining method helps stress transfer, while the roof contacted backfilling is more conducive to stress transfer and failure control. An unloading zone around the stope can be produced by the roof contacted backfill method, which significantly reduces the stress level in the surrounding ore body.

(3) Pressure relief by boreholes and pre-split blasting reveals that good-sized drilling boreholes can reduce stress. However, the effect of using pre-split blasting to form a connected cutting seam on relieving pressure is limited.

(4) In deep shaft construction with a good rock mass quality, the traditional construction process of short excavation and lining early dissipates less energy. It may lead to support failures in a high-stress environment. Increasing the bench height without lining early and determining the proper support time is conducive to the energy prereleasing in the rock mass, which benefits the long-term stability of shaft construction and the reduction of support cost.

(5) In the future, it is suggested to carry out some research studies on how to utilize the high stress for rock breaking, which may reduce the use of explosives and control the ground failures effectively.

Data Availability

The data used to support the finding of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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