Mechanical Analysis of Goaf Processing and Residual Ore Recovery Planning

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Abstract. In this paper, FLAC3D software is used to analyse the overall plan of goaf processing and residual ore recovery. Through the whole process simulation analysis of “underground goaf forming—key goaf filling—residual ore mining”, the plan rationality is evaluated. Results show that: (1) Parts of goaf are in unstable state to some extent. (2) Key goaf pre-filled program is beneficial to improve pillar stress and maintain goaf stability. (3) No massive destruction is caused by pillaring. (4) Pillaring has an impact on the open pit slope stability.

1 Introduction

Usually, area mined-out should be treated is to eliminate gob, to prevent roof rock burst as well as to regulate mined pressure. Either improper action without addressing the mined-out area or just leave the supporting pillars or other treatment, roof rock burst occurred ultimately. Datong experience was got as forecast. Jiangxi Pangushan, Shouwangfen and Xi mining found painful lessons as well as Jingxiang Liuichong phosphate rock [1-2]. In 2011, similar mining disasters were reported in such mining industry developing countries as South Korea and others [3-4]. In recent years, with the development of efficient construction blasting, scale filling materials have made breakthrough as well. However, goaf processing method still generally based on the following four methods. Caving method means caving surrounding rock fill mined-out area. Mining stope method are widely used in subsequent focus goaf at home and abroad [5-6]. Caving isolation method is in the implementation process of caving gradually formed. Caving method in isolation of the old mining once applied in Tongling and Zhongtiaoshan, China. In recent years, treatment of mined areas were mainly focused in roof subsidence monitoring, dynamic and cavability analysis worldly [7-9]. In a narrow sense, filling method refers only to the method of mined-out area filling from inside or outside of waste rock, sand, tailings and others by vehicle or transport pipeline. Broadly speaking, filling method furtherly means filling with waste, fly ash, natural accumulation of water, waste water and others filling into the mined-out area. To achieve sustainable development, environmental protection and pollution-free, we should strive to build nuclear power plants, workshop or laboratory with mined-out area, also used for burial of production waste, storage of garbage, nuclear waste or waste water [10]. Almost when mining industry appeared in the 18th century, a useful support goaf treatment was reported [11]. Practice has proved that the pillars supporting the roof just temporarily alleviate the pressure behavior during the exploitation of land. Roof collapse or roof rock burst occurred can not generally avoid in a long-term unless the recovery rate is enough low [12]. Use of closed isolation method, workers were guaranteed from the air shock wave interference once the roof fall, even equipment, and systems from caving mining excited. Usually, accidents can be prevented when people straying into mined-out area. In addition, leakage or air mixing occurs can be avoided the mine ventilation with this technology [13].

Reclamation is complex system engineering. Especially when the safe production conditions are relatively high. To ensure fool proof reclamation, such process as remnant ore mining sequence requires meticulous [14]. Different mining sequence adopts with different loading and unloading paths. At the same time, there are different variations of stress field and displacement field. Thus, different mining sequence of stope stability results in different effects [15]. Any little stress change or transfer will have a significant impact on the stability of the stope. Reasonable recovery program will significantly improve the stress distribution of rock. To find a reasonable mining sequence is helpful to reduce stope stress, and to improve the stability of the stope [16-17].

In this paper, three-dimensional numerical simulation software FLAC3D is used to analyse stress distribution and displacement trends under goaf processing and residual ore recovery planning. Material is expressed
through the unit and regional representation, the respective grid is computed based on the shape of the object. Each unit mechanically responds in accordance with the agreed linear or nonlinear stress—strain relations under external load and boundary conditions. FLAC3D software is the rock mechanics calculation program primarily adapted for geotechnical engineering analysis. It includes the special calculation function reflecting mechanical effects of geological materials. It can well calculate highly nonlinear of geological materials (including strain hardening/softening), irreversible shear stress damage and compaction, viscoelastic (creep), stress-fluid coupling and thermo-mechanical coupling of porous medium, and dynamics problems. Thus, FLAC3D can calculate the reasonable filling and mining sequence to guide mine safety production.

2 Primary Plan of Goaf Processing and Residual Ore Recovery

2.1 Overview

Niujuan Silver-Gold Deposit is mined from surface to underground. For open stope method mainly applied previously, a large number of irregular goafs come into being currently in the level of 1190m, 1150m and 1110m, which threat to mining safety production. Meanwhile, a lot of high-grade rib and crown pillars remain in goaf, with considerable economic benefits on reclamation. Therefore, a reasonable plan on goaf management and residual mining has great significance for safety production and fully recycling resources.

2.2 Primary Plan

Currently, the goaf and ore pillar have formed framework of regional stability. Residual mining will break the balance of the original structure. Thus, the key goaf should be first filled, which could avoid causing chain-catastrophe due to the instability of partial goaf. Secondly, reclamation should base on eliminating risk in key goaf and ensuring the overall stability of mine.

The primary plan of goaf processing and residual ore recovery is shown as follows:

1. Based on rock mechanics parameters, the stability of every gob is analysed and evaluated with numerical simulation. Then, the key goafs (which is unstable and has a significant impact on the whole stability of mine) are determined. All key goafs must be filled before residual ore mining.

2. The key goafs filling are in accordance with the following sequence: from bottom to up among different stages and in order of importance and emergency according to unstable state at the same level.

3. Analyzing and assessing the stability of mine after all key goafs filled, then considering recycling residual ore on the basis of overall security and stability.

4. Non-critical goafs filling are in coordination with residual orebody stoping. Residual mining sequence: Among different stages, from bottom to top in the rib pillar area and top to bottom in the residual mining area of non-rib pillar. At the same level, in consideration of rib pillars mainly distributing in the central region of orebody, residual mining adopts stoping back from both sides to the middle emergency exit in order to play a supporting role in mine stability as long as possible.

2 Filling sequence of non-critical goafs: Filling sequence vary with subarea and substep of residual area, and the corresponding non-critical gobs have been filled which affecting the safety of the remaining partition before its mining.

The key goafs (green wireframes) and main mining subareas (blue wireframes) are shown as Figure 1.

3.1 Simulation Content and Requirements

FLAC3D was adopted to model and analyze the primary plan of goaf processing and residual ore recovery. Through the entire process inversion of present situation forming, goaf filling treatment and remaining ore recovery, the stability of mined-out area, filling body and residual ore at the whole mine is analysed. Then, the rationality of overall planning is evaluated. Numerical simulation content includes:

1. Simulating the forming process of open pit and existing goaf according to historical excavation sequence, and analysing stability of every gob at present.

2. Simulating the stability state after key goafs filled at whole mine, especially intensively monitoring residual ore mining area.

3. Simulating the overall stability during the process of non-critical goaf filling and collaborative residual mining.

3.2 Model Building

To comprehensively and objectively reflect the process of goaf disposing and residual ore mining. 3D model is built after considering ore body, surrounding rock distribution and certain boundary effect. Model range and diagram is shown as Figure 2.
3.3 Stability Analysis of Current Goaf

3.3.1 Stress Analysis

The ore region's maximum and minimum principal stress clouds are shown as following (Figure 3). From Figure 3, in initial state, the maximum principal stress distribution of ore region is increasing from top to bottom. The maximum principal stress on the top is about -3MPa ("-" indicates compression stress). The maximum principal stress on the bottom is about -7MPa. After open-pit mining finished, low stress zone is shown at the bottom part of the model on the left (north side). After goaf forming, little changes occurred in the overall stress. However, stress concentration exists in the model internal. After stress concentration, the maximum principal stress reaches -36.5MPa, the minimum principal stress reaches -12.0MPa.

After goaf forming, maximum and minimum principal stress clouds are found as following (Figure 4). As figure shows, stress concentration is found in top and sill pillar of some goafs (wireframes range) influenced by excavation. The maximum principal stress reaches -18.1MPa. Part of the region appears stress relief. The maximum principal stress changes from compressive stress to tensile stress, of about 7.1MPa at maximum.

According to the stress concentration region, the stress situation around goaf is analysed with such three typical sections of y = 680, y = 560, y = 390 (Figure 5). It can be clearly seen that there is stress concentration on the hanging wall. Stopes are mined out upper and lower of 1150m level, thus stress concentration is more evident on top pillar, hanging wall and footwall at stage of 1150m and 1110m (Figure 5c). In view of maximum and minimum principal stress changes, open-pit mining has a certain influence on top and north side of orebody near the pit bottom. The stress has changed there as well. After the goaf forming, the stress concentration in crown and sill pillar is obvious, especially more prominent in the roof of large scale goaf and small sill pillar. It shows that these parts prone to damage.
3.3.2 Displacement Analysis

Vertical displacement after open-pit mining and goaf excavation is shown as following (Figure 6). As it can be seen from the figure, displacement or deformation is found surrounding rock towards goaf. The roof displacement is downward and floor upward, mainly vertical displacement or displacement. The hanging wall and footwall move towards goaf mainly in the form of lateral displacement. Due to the influence of open-pit mining, overall vertical displacement is small in roof of goaf near the pit bottom. The pillar between upper and lower goafs appears upward displacement or deformation on footwall and downward on hanging wall, so that the pillar is in the state of shearing stress.

Figure 5. Typical cross-sections of maximum and minimum principal stress clouds.

Figure 6. Vertical displacement contours of ore region.

Typical cross-sections of vertical and horizontal displacement contour are shown as following (Figure 7). As it can be seen from the figure, displacement or deformation is found surrounding rock towards goaf. The roof displacement is downward and floor upward, mainly vertical displacement or displacement. The hanging wall and footwall move towards goaf mainly in the form of lateral displacement. Due to the influence of open-pit mining, overall vertical displacement is small in roof of goaf near the pit bottom. The pillar between upper and lower goafs appears upward displacement or deformation on footwall and downward on hanging wall, so that the pillar is in the state of shearing stress.

Figure 7. Typical cross-sections of vertical and horizontal displacement contours.
3.3.3 Plastic Zone

After the open-pit mining and goaf excavation, overall regional distribution of plastic zone is shown as following (Figure 8). As can be seen, the bottom and local slope of open-pit go into plastic zone after open-pit mining. With goaf forming, slope surface and pit bottom damage to a certain extent by the impact of underground mining. Based regional distribution of plastic zone in the orebody (Figure 8c), it can be seen that surface destruction of pit slope does not extend down to the goaf. But more plastic zone is found in the goaf near pit bottom. It shows that the open-pit mining has some adverse effects on the section near the pit bottom. But protected by the ore pillar and filling pillar, the pit bottom does not generate a large range of plastic zone. Distribution of plastic zone in other region basically follow the law: the larger-scale goaf, the more extensive distribution of plastic zone.

Figure 8. Map of plastic zone distribution.

According to the plastic zone statistics, plastic zone run through the pillar between C901 and C506. At the same time, with local plastic zone on the hanging and foot wall as well. Pillar plastic zone is found between C512, C513 and C104. C505 plastic zone occurs through the roof, and hanging wall appears partly plastic. There is more plastic zone on C903 footwall. Further, plastic zone is found in the roof of C904, C905, C504, C508, C509, C510 and C102 as well as local hanging wall.

3.4 Stability Analysis after Key Goaf Filled

Mine stability is analysed according to previously key goaf filling program. Principal stress cloud of post-filling is showed as following (Figure 9). As it can be seen from the figure, a certain low stress areas form within filling body after goaf filled. Stress concentration in top and sill pillar eases to some extent. It shows that filling body play a role in improving the stress state of rock, bearing some stress as well.

Figure 9. The maximum and minimum principal stress clouds after key goafs filled.

The vertical displacement in the orebody after key goafs filled is showed as following (Figure 10). As can be seen from the figure, concentration of vertical displacement in top pillar eases after key goafs filling. Also, the entire orebody does not appear highlighted vertical displacement or centralized situation.

Non-cemented filling bearing stress generates a larger displacement or deformation. However, it does not mean filling body damaged.

Figure 10. The vertical and horizontal displacement contours after key goafs filled.

Distribution of plastic zone in orebody after key goafs filled is shown as following (Figure 11). As can be seen, most of the plastic zone around goaf has disappeared after filled. It proved that the backfill has worked. After key goaf filled, surrounding rock of each mining area has withdrawn from plastic zone. It indicates that key goafs filling is in favor of residual ore mining safety.
3.5 Rock Stability Analysis of Residual Ore Mining Process

Residual pillars are gradually mining as recovery programs. Maximum and minimum principal stress of ore region is shown as following (Figure 12). As can be seen, after pillars mining and filling, low stress zone is forming in the filling body. Stress in non-mining pillars are increasing slightly, but no significant stress concentration takes place. Backfill bears the maximum and minimum principal stress of about -2.0MPa. It is indicated that the filling body eventually play a role in improving the stress of surrounding rock.

Because of the smaller elasticity modulus, non-cemented backfill will produce larger displacement or deformation in less stress. By its own gravity and surrounding rock stress, greater vertical displacement is found within filling body.

Plastic zone distribution after residual ore mining is shown as following (Figure 13). As can be seen, there is not much plastic zone in the entire orebody except for individual untreated goaf. It indicates that the residual ore mining process does not cause widespread instability.

After residual ore mining, mining 2, 3, 5, and 6 filling body or surrounding rock partically appear plastic zone, but not with other mining area. It shows that surrounding rock is basically stable in mining process on the whole, and shear failure may occur locally. It is suggested that certain pretreatment measures should be taken against the surrounding rock destruction when necessary.

Furthermore, according to comparative analysis of plastic zone in the open-pit before and after residual mining, plastic zone on surface has increased after remnant ore recovery. It indicates that residual ore mining process has an impact on the pit slope. It is recommended that personnel and equipment are not allowed into the pit.

Conclusions

In this paper, numerical simulation is used to establish three-dimensional numerical model. According to the general order "initial stress state simulation—Open-pit mining—Underground goaf forming—Key goaf filling—Residual ore mining", simulation analysis is processed. The main conclusions of this paper are as follows:

1. Early open-pit mining has an impact on the stress distribution of the pit bottom. Meanwhile, early opencast mining affects the stability of latter goaf.
2. Gob C901, C903, C904, C905, C504, C505, C506, C508, C509, C510, C512, C513, C104 and C102 are in unstable state to some extent.
3. Key goaf pre-filled program is beneficial to improve pillar stress and maintain goaf stability.
4. No massive destruction is caused by pillaring. Some damage is found in non-cemented backfill and surrounding rock partially.
5. Pillaring has an impact on the open pit slope stability, it is recommended to avoid personnel and equipment into the pit.

References


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