Numerical Simulation Study of ground surface subsidence caused by filling mining on surface buildings and facilities in a mining area: a case study

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Abstract. The filling mining method is planned to be adopted in Chentaigou Iron Mine. There are many significant buildings and facilities in the mining area, making it necessary to evaluate the influences of underground mining on the surface buildings and facilities. The main purpose of this research was to evaluate the extent of the surface subsidence basin and the degree of damage of buildings and facilities after filling mining by numerical simulation. To this end, a three-dimensional numerical model of the whole mining area was established. Secondly, a Discrete Fracture Network (DFN) in 3DEC numerical simulation software was adopted to obtain the strength parameters of each representative elemental volume (REV). Furthermore, FLAC3D numerical simulation software was utilized to evaluate the range of influence of the surface subsidence basin after filling mining. Finally, the maximum major principal strain on the surface was calculated. The results show that the surface subsidence basin of underground mining in this iron mine undergoes slow expansion then rapid expansion. Expansion of the surface subsidence basin is restricted by fault F1. After the mining orebody, the maximum major principal strain of surface meets design requirements, and the surface buildings and facilities are deemed safe.

Keywords: filling mining method; underground mining; numerical simulation; surface subsidence

1. Introduction

Mineral resources are of great significance to promote social development. With the rapid development of society, the demand for mineral resources increases rapidly. The caving method is widely applied in many metal mines because of its low mining cost. However, the caving method will cause severe stratal movement, which can harm the environment on the surface of the mining area\cite{1-3}. Compared with the caving method, the filling method has unique advantages in controlling the movement of rock strata, so the application of the filling method has steadily increased in recent years. At present, the problem of strata movement caused by caving mining has been studied by many scholars to good effect\cite{4-6}. The backfill is necessary to control the movement of rock strata\cite{7-8}. Limited by the short application time, the mechanism of surface strata movement caused by backfill mining is still under investigation\cite{9-11}.

The Chentaigou Iron Mine is a metal mine that is planned to be mined by the filling method. To provide a reference for the relocation of residents and the location of industrial site, the movement of strata on the surface after filling and mining needs to be assessed. In the present research, a three-dimensional numerical model of the mining area was established through on-site geological investigation and data collection. On this basis, FLAC3D was utilized to simulate the whole process of underground mining in the Chentaigou Iron Mine, and then the movement of rock strata on the mining area and the damage of surface buildings and facilities were evaluated. The results can provide a reference for the evaluation of strata movement in similar metal mines.
2. Engineering Context

2.1 Engineering Geology

Chentaigou Iron Mine is located in Anshan City, Liaoning Province, China. The filling mining method is adopted in Chentaigou Iron Mine. The mining area is 5 km long in the north-south direction and 3 km wide in the east-west direction. The mining orebody can be divided into five orebodies (Nos I to V). Chentaigou Iron Mine will produce 12 million tons of iron ore annually, making it an important iron-ore production site in China. Geological profile corresponding to No. 4500 line in the mining area is selected for a simple description of its engineering geological context. The mining area has experienced multiple geological tectonic events. Fault structures are widely found, of which the most obvious is fault F1 extending in the north-westerly direction. As shown in Fig. 1, granite is widely found in the hanging wall and the strata overlying the orebody are mainly quartz phyllite and carbonaceous phyllite. To be more specific, carbonaceous phyllites are sandwiched between two quartz phyllite. As the main mining orebody, the average thickness of the Fe1 orebody reaches about 220 m. The iron orebody is sandwiched between two carbonaceous phyllites. Quartz schist is mainly distributed around the iron orebody. According to in-situ drilling data, the integrity of the shallow rock mass in the mining area is poor, and the quality of the rock mass is poor. With increasing depth, the integrity of the rock mass improves.

![Geological profile](image)

Figure 1. Geological profile corresponding to 4500 line in the study area (gr refers to the granite; qph refers to the quartz-phyllite; cph refers to the carbonaceous-phyllite; qsc refers to the quartz-schist).

2.2 Mining Context

The filling mining method is adopted in Chentaigou Iron Mine, and the stope layout of the mining area is shown in Fig. 2: the stope is arranged along the axis of the orebody, and the length and height of stope are 140 m and 80 m, respectively. The vertical orebody direction of stope is divided back to the mining block, and the length of the ore block is controlled between 50 m and 80 m. There are 20 m pillars between adjacent blocks. The two-step mining blocks are divided along the strike direction of the orebody with a width of 20 m and a height of 80 m, the first-step mining
and the second-step mining are arranged at intervals. To increase production, the double horizontal mining method is adopted. To be more specific, the orebody at the -780 m and -1020 m levels are first to be mined. Subsequently, the orebody at the -700 m and -940 m levels are mined, followed by that at -860 m.

Figure 2. Stope layout in the mining area (all dimensions are in meters; No. 1 denotes a pillar; No. 2 denotes a rib pillar; No. 3 denotes a filling body).

3. Numerical Modelling

3.1 Numerical Model

Considering that the problem of surface rock movement is a complex spatial problem, two-dimensional numerical simulation software may be limited in dealing with such problems. As a three-dimensional numerical simulation software based on the finite difference principle, FLAC3D has the characteristics of high calculation efficiency and wide range of application. In recent years, FLAC3D has been applied in geotechnical engineering by many scholars [12-15]. Therefore, FLAC3D was chosen to study rock movements in deep-well mining of Chentaigou Iron Mine. FLAC3D is less efficient in building complex 3-d models, so ANSYS software was adopted for modelling, and the resulting model was imported into FLAC3D through the ANSYS-FLAC3D software to obtain the numerical model shown in Figure 3. Six types of rock masses, including granite, quartz phyllite, carbonaceous phyllite, quartz schist, the orebody, and fault F1, were considered in the 3-d calculation model. The length, width, and height of the model were 5500 m, 3900 m, and 1600 m respectively. Four million elements were used in this 3-d numerical model. The orebody and stope layout in the model can be seen in Figure 4.

Figure 3. 3-d numerical calculation model
3.2 Mechanical Parameters of Rock Mass

Determining reasonable strength parameters of rock mass is the key to ensuring the reliability of numerical simulation results. In this study, a Discrete Fracture Network (DFN) in 3DEC numerical simulation software was adopted to obtain the strength parameters of each Representative Elemental Volume (REV). To determine the REV of the rock mass, a 3-d cube model with a side length of 20 m was established. Under the assumption that the strain rate is constant [16], the model with a side-length of 20 m was confined as if under triaxial test conditions. The confining pressures were set to 1 MPa, 1.5 MPa, 2 MPa, and 3 MPa, respectively (these values can be regarded as minimum stresses and the maximum stress can be computed by plotting stress – strain diagrams). Finally, the rock mass parameters were calculated through use of Mohr circles of stress in Roclab software. The Mohr-Coulomb constitutive law was assigned to the computational model. The specific rock mass parameters can be seen in Table 1. The parameters of the backfill body were selected from the design specifications, and the specific values thereof are listed in Table 2.

3.3 In-situ Stress Field and Boundary Condition

The tectonic stress field was investigated around the mining area. According to in-situ stress test results, the stress state in the Chentaigou Iron Mine can be described by (1):

\[
\begin{align*}
\sigma_{x,\text{min}} &= 0.0306H + 0.1171 \\
\sigma_{z,\text{min}} &= 0.0285H + 0.0361 \\
\sigma_{z} &= 0.0191H - 0.5977
\end{align*}
\] (1)

The tectonic stress field was investigated around the mining area. According to in-situ stress test results, the stress state in the Chentaigou Iron Mine can be described by (1):

The boundary conditions mainly use the nodal velocity constraints, which constrain the nodal velocity values around and at the bottom of the model, and the surface adopts free constraints. The specific boundary conditions are as follows:

1. Fix the surface determined by \( x = 0 \) m and \( x = 5500 \) m, with the x-direction nodal velocity on this surface being zero;
2. Fix the surface determined by \( y = 0 \) m and \( y = 3900 \) m, with the y-direction nodal velocity on this surface being zero;
3. Fix the surface determined by \( z = -1600 \) m, with the nodal velocity in all directions on this surface being zero.
4. Modeling Results

4.1 The Expansion of the Surface Subsidence Basin

According to the mine mining design, Chentaigou Iron Mine is divided into three mining stages: the -780 m and -1020 m levels, the -700 m and -940 m levels, and the -860 m level, respectively. After mining, a subsidence basin will be formed on the surface. Figure 5 shows the contours of surface subsidence at the end of each of the three mining stages: Nos 1 to 7 denote the north winding shaft, service shaft, auxiliary shaft, ramp, the No. 1 main shaft, No. 2 main shaft, and southern shaft, respectively. After mining at the -780 m and -1020 m levels, an elliptical subsidence basin is formed on the surface. The maximum subsidence of the surface occurs directly above the orebody. The north winding shaft and service shaft enter the range of influence of the 20-mm subsidence contour. Due to the presence of fault F1, the 40-mm subsidence contour does not cross the fault. After mining at the -700 m and -940 m levels, the surface subsidence basin is further expanded, and the auxiliary well and ramp also enter the range of influence of the 20-mm subsidence contour. At the same time, the 40-mm subsidence contour crosses fault F1 and extends to the footwall. The surface subsidence basin expands significantly after mining at the -860 m level, specifically in the rapid expansion of the 20-mm subsidence contour. The No. 1 main shaft, No. 2 main shaft, and southern shaft are unaffected by the extent of the 20-mm subsidence contour because they remain far from the main orebody. In summary, it is not difficult to find that the expansion of the surface subsidence basin has experienced a process from slow to rapid expansion. Specifically, when mining the orebodies at the -700 m and -960 m levels, the 20-mm surface contour expands less, but after the -860 m level is mined, the associated subsidence basin expands rapidly.
Figure 5. Contours of surface subsidence after the end of the three mining stages. The three stages shown correspond to depths of: (a) -780 m and -1020 m, (b) -700 m and -940 m, and (c) -860 m.

Figure 6(a) shows the plastic zone of the stope when mining at the -700 m and -940 m levels: although a small-scale plastic zone appears in the stope at this mining stage, the stability of the stope is not impaired. There is a roof with a thickness of 10 m between the -780 m level and the -860 m level, and as mining activities continue, extensive plastic failure of the roof occurs while mining the -860 m level in the orebody (Fig. 6b). The failure of the roof causes the plastic zones between different levels to inter-penetrate, which leads to structural instability of the stope. The structural instability of the stope is the main reason for the rapid expansion of the subsidence basin after mining at the -860 m level.
4.2 Damage of Buildings and Facilities

The surface subsidence process after deep mining in Chentaigou Iron Mine was studied; due to the special metallogenic mechanism prevailing therein, metal mines usually have obvious tectonic stress fields. The safety of surface structures in the mining area is not only an indicator of surface subsidence, but the maximum major principal strain of the surface exerts an important influence on surface structures[17-19]. To obtain the maximum major principal strain of the surface, the displacement information of the surface nodes in the numerical simulation calculation results was extracted, and then the horizontal displacement field of the surface was obtained. The horizontal displacement field is finally expressed as \( \mathbf{\mu} = (\mu_x, \mu_y, x_1, y_1) \), where \( \mu_x \) and \( \mu_y \) are the displacements of the surface nodes in the x and y-directions, respectively. Considering that the mining depth of Chentaigou Iron Mine is relatively deep and the backfill mining method is adopted, the surface displacement is relatively small. Therefore, (2) can be used to find the surface horizontal strain. Furthermore, the solved surface strain is expressed as the second-order tensor form of (3). On this basis, the problem of determining the maximum major principal strain on the surface is transformed into the eigenvalues of (3).

\[
\begin{align*}
\varepsilon_x &= \frac{\partial \mu_x}{\partial x} \\
\varepsilon_y &= \frac{\partial \mu_y}{\partial y} \\
\gamma_{xy} &= \frac{\partial \mu_x}{\partial y} + \frac{\partial \mu_y}{\partial x}
\end{align*}
\]

(3)
\[
\varepsilon = \begin{bmatrix}
\varepsilon_x & \gamma_y/2 \\
\gamma_y/2 & \varepsilon_y
\end{bmatrix}
\]  \hspace{1cm} (4)

\(\varepsilon_x\) denote the strain in x-direction; \(\varepsilon_y\) denote the strain in y-direction; \(\gamma_y\) denote the shear strain.

Based on the above analysis, contour of maximum major principal strain after the end of mining can be obtained. Fig. 7 demonstrates that after the end of mining, the maximum major principal strain is distributed in an elliptical shape, and the maximum compressive strain of 0.03 mm/m is generated on the overlying surface of the mined-out area, and tensile strain with a maximum value of 0.002 mm/m is generated at the edge of the mined-out area. The above calculation result is far less than the 2 mm/m allowed in the specification, which shows that the surface buildings and facilities around the mining area are safe.

Figure. 7. Contour of maximum major principal strain after the end of mining. Nos 1 to 7 denote the north winding shaft, service shaft, auxiliary shaft, ramp, No. 1 main shaft, No. 2 main shaft, and southern shaft, respectively.

5. Conclusion

Combined with the analysis of the aforementioned numerical simulation results, the following conclusions were drawn:

1. After the Chentaigou Iron Mine is mined, an elliptical subsidence basin will be formed on the surface, and the expansion of the subsidence basin develops slowly at first, then rapidly. In the initial mining stage (mining of the -780 m and -1020 m levels, and -700 m and -940 m levels of the orebody), the plastic zone in the stope within this range is small; with the progress of mining activities, the stope produces a large-scale penetrating plastic zone at the -860 m level, which leads to the rapid expansion of the surface subsidence basin at this stage. The structural instability of the stope is the main reason for the rapid expansion of the subsidence basin after the mining at the -860 m level.

2. The presence of fault F1 causes significant asymmetry in the surface subsidence basin, as manifest by the expansion of the surface subsidence basin in the hanging wall being more severe than that in the footwall. The extension of the surface subsidence basin to the footwall is limited by the presence of fault F1.

3. The maximum major principal strain on the surface is elliptical and is compressive close to the mined-out area, with tensile strain recorded far from mined-out area. According to the calculated results, the maximum strain is only 0.03 mm/m, which is much less than the allowable 2 mm/m specified initially: the surface buildings and facilities are deemed safe.
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