Mechanical model of safety thickness for resource recovery of complex & difficult mining ore body

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Abstract. In view of the difficulty in calculating the safe thickness of complex and difficult-to-mine orebody in the process of resource recovery, based on the elastic-plastic theory and mechanics method, the mechanical models of the safe thickness of orebody recovery above the collapse area and that of orebody recovery at the side of the collapse area are constructed respectively. The results show that: 1. Using the fixed beam model to calculate the safety thickness, the additional load on the roof, the volume weight and span of the rock stratum, the width of the rock stratum and the water pressure are the important influencing factors. When the water pressure exists, the safety thickness can be reduced; 2. When the safety thickness is calculated by the elastic plate model with fixed support around, the safety thickness decreases with the increase of the tensile strength or shear strength of rock mass, and increases with the increase of the external load; 3. When the collapse area is located at the side of the ore body to be mined, the safety thickness decreases with the increase of the tensile or shear strength of rock mass, and with the increase of the external force. The load increases with the increase of load. The research can provide theoretical support for mining residual mineral resources.

1. Introduction
Safe and efficient green mining is the key to ensure the sustainable development of mines. For some existing mines, due to the collapse and subsidence of stopes caused by disorderly mining in the earlier stage, how to exploit mineral resources in this area deserves attention [2~3]. In the mining design and construction of the orebody in the collapsed area, because there is a collapsed stope below the goaf, the ore body above the mining collapsed area must have a certain safety isolation protective layer not to be mined [4], so as to ensure the safety of personnel and machines, and how to determine the safe thickness between the collapsed area and the goaf is one of the key factors to achieve safe and efficient mining in engineering practice [5-6]. Moreover, the choice of safe distance is directly related to the engineering benefit and quality of mining, so selecting reasonable safe thickness is very important for the safe mining of the whole collapsed area. If the goaf collapses again in mining, it will have a great impact on the mining of the follow-up orebody. However, because there are many factors involved and there is no precedent for engineering practice in this area [8], there is no reliable analysis and calculation method for determining the appropriate safety thickness between the collapse area and the ore body to be mined.
In view of the difficulty in determining the safe thickness of ore body when recovering the ore body above the collapse area. Firstly, it is assumed that the strata between the collapse area and the orebody to be mined are homogeneous, continuous and isotropic elastic bodies, and conform to the theory of small deformation. By using the criterion of tensile strength and shear strength of rock mass, the calculation method of safe thickness between collapse area and goaf can be obtained.

2. Mechanical Model of Safety Thickness of Preserved Roof

2.1. Fixed Beam Model

(1) When water is not considered

The rock mechanics model between the collapse area and the goaf can be simplified into a fixed beam model, and its stress sketch is shown in Figure 1. There are two kinds of loads on the upper end of the retaining beam, one is the self-gravity distributed uniformly along the length direction of the retaining beam, that is, the self-gravity of rock strata; the other is the additional external loads on the retaining beam during mining, while the additional external loads can be simplified as the concentrated force Q. When a fixed beam is subjected to concentrated load Q, its maximum bending moment is located at both ends of the simplified beam and is expressed by the following formula:

\[ M_0 = \frac{QD}{8} \]  \hspace{1cm} (1)

When the uniformly distributed gravity acts on the upper end of the retained beam, the maximum bending moment of the retained beam can be calculated by the following formula:

\[ M_0 = \frac{\gamma HB_0 D^2}{12} \] \hspace{1cm} (2)

From the above two formulas

\[ M_{max} = \frac{QD}{8} + \frac{\gamma HB_0 D^2}{12} \] \hspace{1cm} (3)

In the formula: \( M_{max} \) is the maximum bending moment of the fixed beam, kN⋅m; Q is the sum of the external concentrated loads acting on the top of the goaf roof, kN; \( \gamma \) is the weight of the strata between the collapse area and the orebody to be mined, kN/m\(^3\); H is the thickness of the strata, m; \( B_0 \) is the width of the strata, m; D is the span of the goaf, M. When the fixed beam is subjected to concentrated load Q, the maximum shear force of the fixed beam is calculated according to the following formula (acting on both ends of the fixed beam)

\[ q_0 = \frac{Q}{2} \] \hspace{1cm} (4)
When a fixed beam is subjected to uniformly distributed gravity (acting on both ends of the fixed beam), the formula becomes

\[ q_0 = \frac{\gamma HB_0 D}{2} \]  

Then the maximum shear force formula of fixed beam is as follows

\[ q_{max} = \frac{Q}{2} + \frac{\gamma HB_0 D}{2} \]  

The safety thickness between goaf and collapse area can be obtained by checking the tensile strength.

\[ H_1 = \frac{\gamma B_0 D^2 + \sqrt{\gamma^2 B_0^2 D^4 + 12 QB_0 D \sigma_T}}{4 B_0 \sigma_T} \]  

By checking the shear strength, the safe thickness between the goaf and the collapse area can be obtained as follows.

\[ H_2 = \frac{\gamma B_0 D + \sqrt{\gamma^2 B_0^2 D^2 + 2 Q \tau_T}}{\tau_T} \]  

Formula: T is the tensile strength of rock, MPa; T is the shear strength of rock, MPa, the value of which can be selected as 1/10 of the compressive strength.

(2) When considering the action of water

Assuming that the water pressure PS (kN/m) in the orebody acts uniformly on the top of the goaf roof, the other conditions are the same. Then the maximum bending moment formula of the fixed beam is as follows.

\[ M_{max} = \frac{QD}{8} + \frac{(\gamma HB_0 - P_s) D^2}{12} \]  

The maximum shear force formula of fixed beam is

\[ q_{max} = \frac{Q}{2} + \frac{(\gamma HB_0 - P_s) D}{2} \]  

According to the check of tensile strength, the safety thickness between goaf and collapse area is as follows

\[ H_1 = \frac{\gamma B_0 D^2 + \sqrt{\gamma^2 B_0^2 D^4 + 4 B_0 D \sigma_T (3Q - 2P_s D)}}{4 B_0 \sigma_T} \]  

According to the shear strength test, the safe thickness between goaf and collapse area can be obtained as follows
According to the above, when the collapse area is located at the bottom of the orebody to be mined and the mechanical model between the collapse area and the orebody to be mined is simplified to a fixed beam model, the main factors affecting the safe thickness can be obtained.

2.2. Four-Circumferential Fixed Plate Model
The mechanical model of rock strata in collapse area and goaf area is simplified to the elastic plate model with fixed support around, as shown in Figure 2 below.

\[
H = \frac{\gamma B_0 D + \sqrt{\gamma^2 B_0^2 D^2 + 2(Q - P)D} \tau_T}{\tau_T} \quad (12)
\]

Figure 2. Simplified schematic diagram of the clamped around the board model

It is assumed that the dead load \( g \) acting on the upper end of roof stratum in goaf and the additional load \( Q_s \) generated during construction are evenly distributed on the retaining plate. When the retaining plate is subjected to the uniformly distributed load, the maximum bending moment will occur at the middle point of the long side of the retaining plate. Then the maximum bending moment and the maximum tensile stress of the clamped plate are

\[
|M_{\text{max}}| = \alpha Q C^2 \quad (13)
\]

\[
\sigma_{\text{max}} = \frac{6}{H^2} |M_{\text{max}}| = \frac{\alpha Q C^2}{H^2} \quad (14)
\]

In the formula, \( C \) is the short side length of the fixed plate, \( m \); the load concentration \( Q_s \) of the fixed plate can be expressed by the combined force of the self-weight load \( g \) of the fixed plate and the construction external load \( F_s \); \( D \) is the long side length of the fixed plate, \( m \); and \( \alpha \) is the shape factor, which can be expressed by \( C/D \). According to the tensile strength condition, the safety thickness of goaf and collapse zone is verified as follows

\[
H = \frac{\alpha Q C^2}{\sigma_T} \quad (15)
\]

Considering that groundwater will weaken the strength of rock mass, similarly, the safety thickness calculated by the above formula should be multiplied by a certain safety factor \( N \) and selected according to the surrounding rock conditions.

3. Safety Thickness Mechanics Model for Side Ore Recovery
When mining the orebody on the side of the collapse area, the strata between the collapse area and the orebody to be mined can be simplified to an elastic plate model for analysis, and the water pressure
acting between the collapse area and the orebody to be mined and the pressure generated by the filling body can be simplified to a uniform load on the diagenetic layer, as shown in Figure 3 below.

![Figure 3. Diagram of the rock stratum between collapse area and stay ore body](image)

At this time, the maximum normal stress and shear stress of rock slab are respectively

$$\sigma_{\text{max}} = \frac{3DQ}{CH^2} + \frac{Q}{5D}$$  \hspace{1cm} (16)

$$\tau_{\text{max}} = \frac{3Q}{2CH}$$  \hspace{1cm} (17)

In the formula, the maximum normal stress, MPa; the maximum shear stress, MPa; Q is the uniform external load, kN; H is the thickness of the slab, m; C is the width of the slab, m; D is the excavation height of the goaf, M. The safety thickness of goaf and collapse zone can be obtained by checking the tensile strength condition.

$$H_1 = D\sqrt{\frac{15Q}{(5D\sigma_t - Q)C}}$$  \hspace{1cm} (18)

If the shear strength condition is checked, the safe thickness of goaf and collapse zone can be obtained as follows.

$$H_2 = \frac{3Q}{2B_0\tau_t}$$  \hspace{1cm} (19)

The maximum safe thickness between collapse area and goaf is $H_1$ and $H_2$. Considering the weakening effect of groundwater and other factors on the strength of rock mass and the safety reserve coefficient, the selected safety thickness should be multiplied by a certain safety factor. Analyzing the formula 18 and 19 for calculating the safety thickness of collapse area when it is located on the side of the orebody to be mined.

4. Conclusion

When the mechanical model between the collapse area and the strata of the orebody to be mined is simplified into a fixed beam model, the factors affecting the safety thickness mainly include the additional load acting on the roof of the goaf, the volume weight of the strata between the collapse area and the orebody to be mined, the span of the goaf, the width of the strata between the collapse area and the goaf area and the water pressure in the orebody. When appropriate water pressure exists, the safety thickness can be reduced, and the risk of rock instability can be reduced. Simplify the mechanical model
of rock stratum between collapse area and goaf area into the elastic plate model with fixed support around it. When the collapse area is located at the bottom of goaf, the volume weight of rock stratum between collapse area and formed goaf area, the width of rock stratum, the mining span, the action of external force, the tensile and shear strength of rock stratum, Poisson's ratio of rock mass, and the elasticity of rock mass. Modulus is an important factor affecting safety thickness. Safety thickness decreases with the increase of tensile strength or shear strength of rock mass and increases with the increase of external load. The main factors affecting the safety thickness of the collapse area when it is located on the side of the ore body to be mined include: groundwater pressure and filling pressure, mined-out area excavation temple, rock width, rock tensile and shear strength; the safety thickness decreases with the increase of rock tensile or shear strength, and increases with the increase of external load.

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