Analysis on safe thickness of the horizontal separation pillar in the upward horizontal slicing and filling method

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Abstract. In the mines employing the upward horizontal slicing and filling mining method, it is necessary to set up a horizontal separation pillar in the middle transportation section. Too small a separation pillar may cause the roof to fall in the lower stope, damaging the transportation facilities in the middle section, and affecting the mining safety. Conversely, excessive thickness of the separation pillar will lead to the waste of mineral resources, reducing the economic benefits; therefore, the parameter optimization of horizontal separation pillar in the mining area remains a major safety and technical issue in upward horizontal slicing and filling mining. Taking the separation pillar in the middle section of an iron mine as the research object, various methods, including engineering analogy, theoretical calculation, and numerical simulation were used to comprehensively analyze the stability characteristics of the horizontal separation pillars with different thicknesses and determine the optimal thickness. For the stope with a span of 15–30 m mined with upward horizontal slicing and filling method in domestic and foreign mines, the thickness of horizontal separation pillar is 20–30 m, as analyzed using the engineering analogy method. Based on various theoretical formulas, such as the thickness-span ratio method, load transfer intersection line method, structural mechanics method, and others, the safety thickness of the separation pillar is calculated as 12–24 m with a safety factor of 1.50. According to a numerical calculation model established on the basis of measured drawings of stope and haulage roadways, the minimum safe thickness of the separation pillar is calculated as 23 m by the finite element analysis for typical sections. Based on the rock mass conditions and mining status of the iron mine, the thickness of horizontal separation pillar in the middle mining area is recommended to be no less than 23 m through a comprehensive analysis of empirical analogy, theoretical calculation, and simulation verification. The analysis results can provide a reference for the subsequent structural parameter adjustment and have a guiding significance for improving the comprehensive economic benefits of the mine.

1. Introduction

For mines utilizing the upward horizontal slicing and filling mining method, it is necessary to set up horizontal separation pillar in the middle transportation section. If the separation pillar size is too small, it is easy to induce roof fall in the lower stope, damage the transportation facilities in the middle section, and affect mining safety. Excessive thickness of the separation pillar will lead to the waste of mineral and economic resources; therefore, parameter optimization of horizontal separation pillar in
the mining area remains a major safety and technical issue in upward horizontal slicing and filling mining [1-3].

For upward horizontal slicing filling method, roof management is the most important link. Because of its unique mining technology, equipment and personnel are required to complete rock drilling, charging and ore drawing in the stope. The stability of stope roof is directly related to the safety of equipment and personnel, mining production, and other aspects. For a long time, experience and engineering analogy methods are often used in engineering practice [4-5]. No matter the method, people tend to evaluate safety in practice. Due to different development degrees of stope-surrounding rock and structural plane in the ore body, the influencing factors become variable and unpredictable. It is difficult to use a mechanical model to determine the stope roof stability. Even if the maximum safety factor is used as the basis of roof management, it cannot guarantee the absolute safety and reliability of the roof [6-8]. The structural parameters of stope are closely related to the stability of the surrounding rock and mining methods. Different mining methods determine different excavation sequences with multiple engineering excavation results in variable stress distribution. With the development of science and technology, computer simulation can be used to achieve experimental results for a complex scientific calculation. Goodman and Brown introduced the concept of numerical simulation in rock engineering; combined with elastic theory and finite element analysis method, it gradually developed into the widely used Mohr–Coulomb model [9-10].

The selection of stope structural parameters depends on various factors, such as the dip angle, thickness and stability of the ore body and surrounding rock, the geological structure of the mining area, and the importance of structures near the goaf. Although many miners have vast experience in selecting the structural parameters, there is not one parameter that is suitable for multiple mines; therefore, when determining the structural parameters of a certain deposit, it is necessary to analyze the specific situation.

The typical horizontal separation pillar of an upward horizontal slicing mining mine is shown in Figure 1.

![Figure 1. Schematic diagram of the horizontal separation pillar](image)

As shown in Figure 1, the haulage roadway is arranged at −320 m level. According to the development and utilization plan, a 53 m thick horizontal separation pillar is set between −305 m and −358 m levels. The upper part above the horizontal separation pillar is the stope filled after each slice mined from −305 m level, and the lower part is the stope filled after each slice mined from −400 m level. There are two main purposes for setting the horizontal separation pillar, one is to ensure the independent and safe mining of the upper and lower stopes of the separation pillar, another is to ensure the safety of −320 m horizontal haulage roadway with uninterrupted ore drawing.

Due to the stope operation above and below the horizontal separation pillar, the deformation and collapse of rock strata threaten the personnel and equipment; thus, the safety of the separation layer will directly determine the safety of underground mining.
If the separation layer is too thin, the surrounding rock of the goaf might suddenly collapse, having a strong dynamic impact on the underground goaf and possibly damaging the main haulage roadway at −320 m level, affecting the safety production of the mine. If the separation layer is too thick, it will inevitably cause a waste of the mineral resources leading to great economic losses. Therefore, combined with the current situation of mining, the optimization of isolated pillar parameters in the mining area is a major safety and technical problem that needs to be solved urgently. It is of great guiding significance to promote sustainable, safe, and efficient mining and improve the comprehensive economic benefits of the mine\textsuperscript{[11-12].}

2. Empirical analogy of the thickness of the separation pillar

Referring to the experience of similar mines at home and abroad, empirical analogy is the most common method used to determine the stope structure parameters after classification and comparison. Because the analogy method is simple and convenient, it is widely used in the selection of mine parameters.

First, the maximum span of the goaf in lower stipes of the separation pillar is counted, and the results are shown in Table 1.

| Stope number | North side | Middle part | South side | Average |
|--------------|------------|-------------|------------|---------|
| 1            | 18.63      | 13.98       | 10.42      | 14.34   |
| 2            | 13.52      | 50.36       | 22.28      | 28.72   |
| 3            | 32.02      | 32.84       | 25.31      | 30.06   |
| 4            | 27.22      | 25.45       | 13.35      | 22.01   |
| 5            | 19.14      | 14.15       | 16.25      | 16.51   |
| 6            | 12.16      | 14.93       | 9.62       | 12.24   |
| 7            | 26.81      | 21.96       | 15.64      | 21.47   |
| 8            | 11.45      | 14.82       | 16.54      | 14.27   |

As evident from Table 1, the maximum span of the goaf in lower stipes of the separation pillar is generally between 15 m and 30 m.

The average uniaxial compressive strength (UCS) of rock in this mine is 101.60 MPa. The thickness of the horizontal separation pillar in some domestic and foreign mines with similar UCS is shown in Table 2, which can be used as a reference for determining the thickness of horizontal separation pillar under similar conditions.

| Mine name                  | Stope span/m | Rock hardness coefficient/f | Thickness of horizontal separation pillar/m |
|----------------------------|--------------|-----------------------------|---------------------------------------------|
| Shouwangfen Copper Mine, China | 25–30        | 8–14                        | 24–30                                       |
| Zhangling Iron Mine, China  | 34           | 6–10                        | 24–26                                       |
| Jinling Iron Mine, Shandong, China | 20–30      | 6–12                        | 24                                          |
| Krivorog Iron Mine, Ukraine | 15–25        | 4–14                        | 20–30                                       |
| Nikitovskiy Mine, Russia    | 20–25        | 8–10                        | 15–30                                       |

It can be seen from Table 2 that when the stope span is 15–30 m in mines with similar rock hardness coefficient, the thickness of the horizontal separation pillar in domestic and foreign mines is between 20 and 30 m\textsuperscript{[13-14]}.

3. Theoretical analysis of the thickness of the separation pillar\textsuperscript{[15-16]}

3.1. Thickness-span ratio method

The thickness-span ratio theory and calculation method are shown in formula 1.

\[
\frac{H}{KW} \geq 0.5
\]
Where,

- $H$ - thickness of the safety isolation layer, m
- $W$ - span of goaf, m
- $K$ - safety factor

The thickness-span ratio method calculates the thickness-span ratio according to the approximate horizontal span and the minimum thickness of the separation pillar, which can be used to evaluate safety thickness.

3.2. Load transfer intersection line method

The load is assumed to be transmitted downward at a diffusion angle of $30^\circ$–$35^\circ$ from the center of the roof in a vertical line. When the transmission line is outside the intersection of the roof and the side wall of the goaf, the side wall of the goaf directly supports the external load on the roof and the self-weight of rock, indicating that the roof and rock are safe. The calculation diagram is shown in Figure 2.

![Figure 2. Schematic diagram of the load transfer intersection line method](image)

The load transfer intersection line method is used to obtain the relationship between the different spans of goaf and thickness of the safety separation pillar. The calculation formula is shown as follows

\[ h \geq \frac{L_s}{2 \tan \beta} \]  \hspace{1cm} (2)

where,
- $L_s$ - span of goaf, m
- $h$ - thickness of the safety separation pillar, m
- $\beta$ - angle between the load transfer line and central vertical line of roof

3.3. Structural mechanics method

The safety separation pillar in the upper part of the goaf is assumed as a plate beam with fixed ends in structural mechanics. In the calculation, it is simplified as a problem of plane elastic mechanics, and the unit width is used in the calculation. The calculation diagram and bending moment of the lithologic plate beam are shown in Figures 3 and 4.

![Figure 3. Supporting condition of lithologic plate beam (fixed state at both ends)](image)
According to the mechanical model, the bending moment and stress in the thick beam can be obtained as

\[ M = \frac{(\gamma h + q) l_n^2}{12} \]  

\[ \omega = \frac{bh^2}{6} \]  

where,

- \( M \) - bending moment, N\cdot m
- \( \omega \) - section modulus in bending, m³

The allowable stress (\( \sigma_a \)) of the roof is equal to:

\[ \sigma_a = \frac{M}{\omega} = \frac{(\gamma h + q) l_n^2}{2bh^2} \]  

According to the formula above, the safe thickness of the separation pillar is deduced as

\[ H = 0.2S_n \frac{\gamma l_n + \sqrt{[\gamma l_n]^2 + 8bq\sigma_a}}{b\sigma_a} \]  

where,

- \( H \) - thickness of the separation pillar, m
- \( \gamma \) - bulk density of rock, kN/m³
- \( l_n \) - span of goaf, m
- \( b \) - unit calculated width of the separation pillar, take \( b = 1 \) m
- \( q \) - overburden load of the separation pillar, Mpa
- \( \sigma_a \) - allowable tensile stress of the rock mass, kPa

This method considers the self-weight of roof, overburden load, physical and mechanical properties of rock, and structural weakening coefficient, making it a reliable and practical engineering calculation method.

### 3.4. Summary of theoretical analysis results

The maximum span of the goaf in lower stopes of the separation pillar is between 12 m and 30 m. The thickness of the separation pillar under span of 15–30 m in each stope is shown in Table 3.

#### Table 3. Theoretical analysis results of the separation pillar thickness under different spans

| Span of goaf | Thickness of safety separation pillar calculated by different methods /m |
|------------|---------------------------------------------------------------------|
|            | Thickness-span ratio method | Load transfer intersection line method | Structural mechanics method | Average thickness |
| 15         | 11.3 | 12.0 | 9.3 | 10.9 |
| 20         | 15.0 | 16.0 | 13.4 | 14.8 |
| 25         | 18.8 | 20.0 | 18.0 | 18.9 |
The above theoretical analysis method is based on the roof stability of open stope mining. Under an average stope span of 15–30 m and a safety factor of 1.5, the safety thickness of horizontal pillar obtained by theoretical calculation is between 11 and 24 m.

4. Numerical simulation of the thickness of the separation pillar

In recent years, numerical simulation method has developed rapidly. Because of its comprehensive consideration of various factors, the results are intuitive and visualized; thus, it has become a widely used research method of rock mechanics. According to the failure phenomenon and failure form of separation pillars under different loads, the Mohr–Coulomb yield criterion is adopted to determine the reasonable size of separation pillars by the commonly used, Rocscience Phase 2 geotechnical analysis software.

4.1. Engineering geomechanics model

Based on the principle of appropriate simplification and analysis and considering various factors, including the rock mass quality grade of different stopes, mining exposure area, distance between stope and middle haulage roadway, and pillar size, a typical section is selected to establish the analysis model. The geomechanics model is shown in Figure 5.

\[
f_s = \sigma_1 - \sigma_3 \frac{1 + \sin \varphi}{1 - \sin \varphi} - 2c \sqrt{\frac{1 + \sin \varphi}{1 - \sin \varphi}}
\]

where,

- $\sigma_1$ - the maximum principal stress
- $\sigma_3$ - the minimum principal stress
- $c$ - the cohesive force
- $\varphi$ - the friction angle

When $f_s > 0$, shear failure will occur. In the normal stress state, the tensile strength of rock mass is very low, so tensile failure of the rock mass can be judged according to the tensile strength criterion ($\sigma_3 > \sigma_T$).
Combined with the actual rock conditions in the stope, the stope stability with different separation pillar thicknesses was simulated to determine and verify the theoretical analysis results of separation pillar thickness. Based on the design of horizontal separation pillars, the numerical simulation analysis of mining and filling is completed at an interval of 5 m upward from −358 m level. The optimal pillar thickness is selected according to the influence of different mining heights on the stability of the filling stope above −305 m level and the haulage roadway at −320 m level.

4.3. Mechanical parameters of rock mass
Considering the influence of rock mass homogeneity, joints, fissures, and other factors, the physical and mechanical parameters of engineering rock mass are calculated based on the engineering rock mass classification standard and the Hoek–Brown strength criterion. The specific parameters are shown in Table 4.

| Petrofabric          | Rock mass density $\rho_m$ g/cm$^3$ | Cohesion $c$ MPa | Internal friction angle $\phi^\circ$ | Tensile strength $\sigma_t$ MPa | Deformation modulus $E$ GPa | Poisson’s ratio $\mu$ |
|----------------------|--------------------------------------|------------------|------------------------------------|-------------------------------|---------------------------|---------------------|
| Ore deposit          | 3.3                                  | 1.561            | 35.11                              | 0.580                         | 6.07                      | 0.28                |
| Surrounding rock     | 2.8                                  | 4.2              | 41.0                               | 1.246                         | 8.31                      | 0.25                |
| Filling body         | 1.74                                 | 0.3              | 39.0                               | 0.16                          | 0.38                      | 0.25                |

4.4. Analysis of simulation results
(1) Initial geostress field
The idea of the simulation is establishing the mesh model, and subsequently the rock mass mechanical parameters, and in-situ stress field. Under the correct boundary conditions, the initial mechanical field of Earth is formed by iterative calculation, and the numerical calculation model is consistent with the mechanical state of the research position. Taking the analysis section as an example, the initial in-situ stress field after stabilization is shown in Figure 6, conforming to the distribution law of in-situ measured stress.

![Figure 6. Initial stress distribution of the calculation model](image)

(2) Stress analysis of stope

![Figure 7. Variation of average stress in upward mining at 5 m, 30 m, and 35 m](image)

The average stress increases from 13.5 MPa to 15 MPa, increasing by 10% in the process of upward mining from 5 m to 35 m above the stopes under the horizontal separation pillar.

(3) Analysis of stope displacement
Figure 8. Variation of total displacement in upward mining at 5 m, 30 m, and 35 m
As per the 5 m interval, the total displacement of the horizontal separation pillar gradually increases from 0 mm to 30 mm in upward mining from 5 m to 35 m. When the mining height reaches 35 m, the displacement of the separation pillar rock mass shows the overall connection phenomenon with a maximum displacement of 45 mm.
(4) Analysis of Stope Safety Factor

Figure 9. Variation of safety factor in upward mining at 5 m, 30 m, and 35 m
As per the 5 m interval, the safety factor of the horizontal separation pillar gradually decreases from 1.58 to 0.63 in the upward mining from 5 m to 35 m above the horizontal separation pillar. When the mining height reaches 35 m, the overall safety factor of the horizontal separation pillar decreases below 1.26, and the stability decreases significantly.
According to the analysis results, the limit height is 30 m for upward mining from −358 m level and the thickness of the horizontal separation pillar is 23 m, i.e., the safety pillar between −305 m and −328 m levels can become the minimum safety factor.

5. Conclusions
Through empirical analogy, theoretical analysis, and numerical simulation calculation, the thickness parameters of the separation pillar between −358 m and −305 m levels are optimized. The following conclusions are drawn:
(1) Based on the empirical analogy method of separation pillar thickness, when the stope span is 15–30 m, the thickness of separation pillar in domestic and foreign mines is generally between 20 and 30 m.
(2) Using the thickness-span ratio, load transfer intersection line, and structural mechanics methods, the safety thickness of horizontal pillar calculated using theoretical calculation is between 11 and 24 m under the condition of an average stope span of 15–30 m and a safety factor of 1.5.
(3) The numerical calculation model is established based on the measured drawing of −358 m level and a compound projection drawing of −320 m haulage roadway, and a typical section is selected. The safe thickness of separation pillar is calculated as 23 m via the finite element analysis.
(4) Based on the rock mass conditions and mining status, the separation pillar thickness under −305 m level is determined to be no less than 23 m based on the above methods.

6. References
[1] HE Man-chao, XIE He-ping, PENG Su-ping, et al. Study on rock mechanics in deep mining engineering[J]. Chinese Journal of Rock Mechanics and Engineering, 2005,24(16):2803-2813.
[2] LI Xi-bing, PENG Ding-xiao, FENG Fan, et al. Stability analysis of horizontal insulating pillar in deep mining from caving to filling method on the basis of refined plate theory[J]. *Journal of China University of Mining & Technology*, 2019, 48(3): 484-494.

[3] ZHAO Xing-dong. Stability analysis of insulating pillar of excavation of Chambishi Copper Mine in depth[J]. *Chinese Journal of Rock Mechanics & Engineering*, 2010, 29 (Sup1): 2616-2622.

[4] WANG Li, MING Shi-xiang, ZHANG Yong-da, et al. Application of mechanized upward horizontal slicing and filling continuous mining method in a gold mine[J]. *Mining Research and Development*, 2015, 035(007): 5-8.

[5] PENG Fu-jun, ZHU Tian-ping, WANG Xun-qing. Improvement of upward horizontal slicing and filling mining method in Huogeqi Copper Mine [J]. *Nonferrous Metals (mine section)*, 2012(04): 19-21.

[6] GUO Xiong, QIAO Wei. Application of panel upward horizontal slicing and filling method in Chambishi Copper Mine [J]. *Mining Technology*, 2011, 11(002): 11-12.

[7] ZHOU Ke-ping, SU Jia-hong, GU De-sheng, et al. Nonlinear prediction method for safe roof thickness of orebody mining under complex backfill [J]. *Journal of Central South University (Natural Science Edition)*, 2005(06): 1094-1099.

[8] P.A. Cundall1. Distinct element methods of rock and soil structure[J]. *E.T. Brown, Analytical & Computational Methods in Engineering Rock Mechanics*, 1987, 129–168.

[9] ZHENG You-fu, WANG Hong-wu, ZENG Sheng, et al. Numerical simulation of upward horizontal layered filling mining method based on FLAC3D[J]. *Yunnan Metallurgy*, 2008(04): 10-13.

[10] WANG Xin-feng, GAO Ming-zhong. Mechanical model of fracture mechanism of stope roof for working face with variable length[J]. *Journal of China University of Mining & Technology*, 2015, 44(1): 36-45.

[11] LIU Hong-lei, YANG Tian-hong, XU Hong-liang, et al. Simulation study on schemes for interval ore pillar in Huanren Lead-zinc Mine[J]. *Chinese Journal of Underground Space and Engineering*, 2012, 8(4): 785-790.

[12] TIAN Ming-hua. A study about key technique related to mechanized cut and fill method for slightly inclined deposit with medium thickness[D]. *Central South University*, 2009: 3-13.

[13] E. Hoek, E.T. Brown. Empirical strength criterion for rock masses[J]. *Journal of the Geotechnical Engineering Division, ASCE*, 1980, 106 (GT9): 1013-1035.

[14] Hoek E., Brown E.T. Practical estimates of rock mass strength[J]. *International Journal of Rock Mechanics and Mining Sciences*, 1997, 34(8): 1165-1186.

[15] XIE Sheng-qing. Research of the Huangmailing Phosphate safe and smooth transfer technology from open-pit to underground mining [D]. *Central South University*, 2011: 34-41.

[16] YANG Peng, ZHANG Dong-hong, ZHANG Bing, et al. Stability analysis of safety pillar in transition from open-pit to underground mining in Chambishi Copper Mine[J]. *Industrial Minerals & Processing*, 2017(3): 24-28.

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