Sensitivity analysis of factors influencing pillar stability in the deep stope of underground salt mine

X S Qin1,2*, H Cao1,2 and L J Guo1,2

1 BGRIMM Technology Group, Beijing, China 100160
2 National Center for International Joint Research on Green Metal Mining (NCGMM), Beijing, China 102628

*Corresponding author (Xiushan QIN). Tel.: +86-10-59069602; E-mail address: qinxiushan@bgrimm.com

Abstract. The orebody and the surrounding rock of underground salt mine are generally divided into soft rock or extremely soft rock. In these mines, the strip room pillar method is primarily used. Continuous pillars with a certain width are left between every two mining strips. These pillars are used to provide support to the overlying surrounding rock. However, the stability of the pillars restricts the stope structural parameters of the mining method. Thus, it is important to first determine the main factors that affect pillar stability and analyze the influence level of these factors. Using a deep mining underground salt mine as an example, the characteristics of pillar instability and the pillar load are analyzed. The safety factor of the pillar refers to the ratio of pillar strength to pillar load, which can be used to quantitatively evaluate pillar stability. Based on the formula of pillar stress and the empirical formula of pillar strength, the formula of the pillar safety factor is deduced. Based on this formula, the primary factors affecting pillar stability are comprehensively analyzed. Moreover, the sensitivities of these factors are compared and analyzed based on the orthogonal range theory. According to the calculation results of the range, the factors influencing pillar stability in the underground salt mine are the mining depth and uniaxial compressive strength of ore, which are the most significant factors, followed by the height and width of pillars, and then the room width and unit weight of the overlying strata, which have relatively small influence. The safety factor of the pillar is positively correlated with the pillar width and uniaxial compressive strength but negatively correlated with the mining depth, pillar height, room width, and the unit weight of the overlying strata. The specific reasons of each factor affecting the safety coefficient are analyzed in detail. The changing trend of the pillar safety factor with various influencing factors can provide an important basis for the optimal design of stope structural parameters and the determination of support scheme.

1. Introduction
The strength of orebody and the surrounding rock, which is divided into soft rock and extremely soft rock, of underground salt mine is relatively low. Currently, there is no corresponding design basis for designing the stope structural parameters of underground salt mine. Thus, additional analysis should be conducted according to the mining conditions. The stope structural parameters directly determine the stability of underground stope, which is important for the safe and efficient production of salt mines. The stope structural parameters are primarily restricted by the stability of stope pillars.
Therefore, it is important to analyze the primary factors affecting the stability of stope pillars and determine their level of influence before determining the stope structural parameters. By deducing the formula of the pillar safety factor, the primary factors influencing pillar stability can be determined through the analysis of the physical parameters in the formula. The primary influencing factors of stope pillar stability are determined as per a certain interval within their respective reasonable value range. Through the orthogonal test design, the stope structural parameters are divided, and the safety factor of stope pillar is calculated. To evaluate the level of influence of each factor on the safety factor of stope pillar, range analysis is used. The specific reasons of each factor that affect the safety coefficient are analyzed in detail.

According to the analysis results, it can be determined which factors have a great influence on the stability of stope pillars, which factors have a relatively small influence, and which level of combination of the influencing factors can improve the safety factor of pillars so as to provide an important basis for the evaluation of stope stability and further guide the design of underground salt mine.

2. Orebody conditions and mining method
The basement rocks of an underground salt mine belong to the Proterozoic era, and the upward sequence is Cretaceous system, Neogene system, and Quaternary system. The Cretaceous system can be divided into three sections from the bottom to the top: the lower continental deposit, the middle salt deposit, and the upper marine deposit. The salt deposit in the middle part is the ore-bearing horizon, and the lithology is the interbedding of carnallite and salt rock. The salt layer is, in general, nearly horizontal, and carnallite is the primary ore in the stope. Carnallite ore exhibits a low uniaxial compressive strength and is categorized as soft rock.

The strip room pillar method with mechanical cutting is adopted in the mine. Strip mining is a partial mining method. It divides the orebody into regular strips having a certain width and leaves continuous pillars with a certain width between the mining strips. In this method, the overlying surrounding rock is supported by the isolated pillars left between the strips so as to achieve the purpose of controlling the movement of the surface rock. The specific mining method is presented in Figure 1.

![Figure 1. Schematic of the strip room pillar method.](image)

3. Analysis of the influencing factors of pillar stability

3.1. Pillar failure mode
With the mining of the strip room, the stress of rock mass is redistributed for mines using the strip room pillar method. The pressure of the overlying surrounding rock is primarily supported by the isolated pillars. An isolated pillar is formed by two adjacent mining strips, and the stress borne by the pillar is the result of the superposition of stress concentration formed after strip mining[1-3]. Figure 2 shows the distribution of pillar pressure.
Under the concentrated stress caused by mining, the pillar stability characteristics primarily depend on the physical and mechanical properties of the pillar rock mass, size of the pillar, and reinforcement and support measures taken for the pillar. Figure 3 shows the three main forms of pillar damage.

Figure 3(a) shows the brittle failure mode because of the development of fracture in the pillar rock mass when the stress exceeds its ultimate compressive strength after the compression of low-strength pillar. Figure 3(b) shows the failure mode caused by the large plasticity of pillar rock mass, which is manifested in the large plastic deformation before the pillar is damaged and the obvious lateral size is enlarged. This prominently occurs in underground salt mine. Figure 3(c) shows the failure mode because of a weak structural plane in the pillar when the shear stress generated by pillar compression exceeds the shear strength.

When the load stress of the pillar is small and does not exceed its ultimate strength, the pillar is considered to be in elastic state and remains intact. When the peak stress of the pillar is larger than its ultimate strength, plastic deformation occurs, and then failure occurs with the increase in stress.

3.2. Pillar stress
When the stoping of the strip room is completed, the pressure of the overlying strata is transferred to the isolated pillar; this leads to the occurrence of the stress concentration phenomenon in the pillar. To correctly estimate the load on the pillar, researchers have introduced certain assumptions and theories,
including the effective area theory, pressure arch theory, and area bearing theory\cite{4,5}. Among these theories, the area bearing theory is most extensively used owing to its simple calculation formula. According to the area bearing theory of the pillar, after the strip room mining is completed, the interval pillar is reserved to bear the weight of the surrounding rock within the mining area of the pillar itself and the adjacent stope. The average stress of the pillar is inversely proportional to the proportion of the area supported by the pillar in the sum of mining and pillar area. Based on the area bearing theory and the plane strain simplification, the stress formula of the pillar is obtained as follows:

\[
\sigma_p = \gamma H \left(1 + \frac{W_o}{W_p}\right)
\]

(1)

where
\[
\gamma = \text{unit weight of the overlying rock, kN}\cdot\text{m}^{-3};
\]
\[
H = \text{mining depth, m};
\]
\[
W_o = \text{room width, m};
\]
\[
W_p = \text{pillar width, m}.
\]

3.3. Pillar strength

Studies on pillar strength are primarily based on the field in situ test results\cite{6-8}, which are combined with relevant theoretical analysis to obtain the corresponding empirical formula for calculating pillar strength, such as the Bieniawski formula, Obert–Duvall formula, and Bunting formula. Most of these formulas are based on the research result of coal mine pillars and few on the pillars of underground salt mines. Because the carnallite orebody and coal mine body are both soft rocks, the strength calculation formula of carnallite pillars is obtained by referring to a large number of in situ tests of 66 coal pillars in South Africa by Bieniawski, which have a width to height ratio of 0.5–34.

\[
S_p = \sigma_c \left[0.64 + 0.36 \left(\frac{W_o}{h}\right)^\alpha\right]
\]

(2)

where
\[
\sigma_c = \text{uniaxial compressive strength, MPa};
\]
\[
\alpha = \text{is a constant, which is taken according to the width to height ratio of the pillar (when the ratio is greater than 5, } \alpha = 1.4; \text{ when the ratio is less than 5, } \alpha = 1.0);\]
\[
W_p = \text{pillar width, m};
\]
\[
h = \text{pillar height, m}.
\]

3.4. Pillar safety factor

The safety factor of pillar refers to the ratio of pillar strength to pillar load. Pillar stability can be quantitatively evaluated according to its value. According to the above relevant empirical formula, the safety factor of pillar in strip stope can be calculated using the following formula:

\[
K = \frac{S_p}{\sigma_p} = \sigma_c \left[0.64 + 0.36 \left(\frac{W_o}{h}\right)^\alpha\right] \cdot \gamma H \left(1 + \frac{W_o}{W_p}\right)^{-1}
\]

(3)

where
\[
K = \text{pillar safety factor};
\]
\[
S_p = \text{pillar strength, MPa}; \text{ and}
\]
\[
\sigma_p = \text{average stress of ore pillar, MPa}.
\]
3.5. Influencing factors of pillar stability

According to the above formula of the pillar safety factor for strip stope, the main factors that influence pillar stability include the following six parameters:

- Mining depth ($H$);
- Pillar height ($h$);
- Room width ($W_o$);
- Pillar width ($W_p$);
- Uniaxial compressive strength ($\sigma_c$); and
- Unit weight of overlying strata ($\gamma$).

4. Theory of orthogonal range analysis

Orthogonal experiment design is a scientific experiment design method used to study the combination of multifactors and multilevels. It uses an orthogonal table to arrange multifactors and multilevels experiment reasonably such that each factor level can be balanced and matched. The advantages of this method are that it can reduce the number of times required to complete the test requirements, the tests are more evenly distributed within the range of values, and the test results can be further analyzed using statistical methods, such as range analysis.

When the orthogonal test is used, the level of influence of each factor on the result cannot be determined because each test factor changes within its value range. By comparing the maximum difference between the test results of various factors at different value levels, combined with the range analysis, the primary and secondary influencing factors can be obtained \[9,10\].

In the range analysis and calculation, the number of influencing factors is $n$, and the serial number is $j=1,2,...,n$; the value level of each influencing factor is $m$, and the sequence number is $i=1,2,...,m$.

$K_i$ denotes the safety factor calculated using the corresponding level value $i$ of factor $j$, and $\bar{K}_j$ denotes the average value of safety factors calculated using the combination of parameters under the same level value $i$ of factor $j$. Consider $R_j$ as the difference between the maximum and minimum values of $\bar{K}_j$ at each level, i.e., the range of the factors in column $j$.

$$ R_j = \max(\bar{K}_{j1}, \bar{K}_{j2}, \ldots, \bar{K}_{jm}) - \min(\bar{K}_{j1}, \bar{K}_{j2}, \ldots, \bar{K}_{jm}) $$

(4)

$R_j$ denotes the variation range of the safety factor when the level value of the factors in column $j$ changes. Thus, the level of influence of each factor on safety factors can be determined using the range $R_j$ value of each factor. When the $R_j$ value is larger, it indicates that the greater the influence of this factor on the safety factors, the more important it is.

5. Orthogonal range analysis of the influencing factors of pillar stability

According to the orebody occurrence conditions, mining process requirements, and mining equipment capacity of an underground salt mine in Congo, the six influencing factors of pillar stability of the strip method stope are reasonably taken within their respective application scope, and each influencing factor in the orthogonal test is taken as five different levels, as presented in Table 1.

| Factors                  | Levels | Mining depth $H$ (m) | Pillar height $h$ (m) | Room width $W_o$ (m) | Pillar width $W_p$ (m) | Uniaxial compressive strength $\sigma_c$ (MPa) | Overburden unit weight $\gamma$ ($\text{t/m}^3$) |
|-------------------------|--------|---------------------|----------------------|----------------------|------------------------|-----------------------------------------------|-----------------------------------------------|
| 1                       |        | 240                 | 12                   | 12                   | 12                     | 4                                            | 2.30                                          |
| 2                       |        | 310                 | 10                   | 10                   | 14                     | 6                                            | 2.20                                          |
| 3                       |        | 380                 | 8                    | 8                    | 16                     | 8                                            | 2.10                                          |

Table 1. Test factors and level value of pillar stability calculation.
In Table 1, a total of six influencing factors are presented, five level values are designed for each factor, and $L_{25}(5^4)$ orthogonal table is chosen for calculating the safety factor of pillar and analyzing the orthogonal range. Table 2 shows the different combination schemes of each parameter and calculation results of the corresponding safety factors.

**Table 2. Calculation scheme and results of pillar stability analysis.**

| Test No. | Factors | 1 | 2 | 3 | 4 | 5 | 6 | Safety factors $K_a$ |
|---------|---------|---|---|---|---|---|---|----------------------|
| 1       | $H$     | 1 | 1 | 1 | 1 | 1 | 1 | 0.362                |
| 2       | $h$     | 1 | 2 | 2 | 2 | 2 | 2 | 0.758                |
| 3       | $W_o$   | 1 | 3 | 3 | 3 | 3 | 3 | 1.439                |
| 4       | $W_p$   | 1 | 4 | 4 | 4 | 4 | 4 | 2.688                |
| 5       | $\sigma_c$ | 1 | 5 | 5 | 5 | 5 | 5 | 5.351                |
| 6       | $\gamma$ | 2 | 1 | 2 | 3 | 4 | 5 | 1.170                |
| 7       | $\gamma$ | 2 | 2 | 3 | 4 | 5 | 1 | 1.501                |
| 8       | $\gamma$ | 2 | 3 | 4 | 5 | 1 | 2 | 0.695                |
| 9       | $\gamma$ | 2 | 4 | 5 | 1 | 2 | 3 | 0.940                |
| 10      | $\gamma$ | 2 | 5 | 1 | 2 | 3 | 4 | 1.320                |
| 11      | $\gamma$ | 3 | 1 | 3 | 5 | 2 | 4 | 0.699                |
| 12      | $\gamma$ | 3 | 2 | 4 | 1 | 3 | 5 | 0.792                |
| 13      | $\gamma$ | 3 | 3 | 5 | 2 | 4 | 1 | 1.130                |
| 14      | $\gamma$ | 3 | 4 | 1 | 3 | 5 | 2 | 1.312                |
| 15      | $\gamma$ | 3 | 5 | 2 | 4 | 1 | 3 | 0.728                |
| 16      | $\gamma$ | 4 | 1 | 4 | 2 | 5 | 3 | 0.942                |
| 17      | $\gamma$ | 4 | 2 | 5 | 3 | 1 | 4 | 0.432                |
| 18      | $\gamma$ | 4 | 3 | 1 | 4 | 2 | 5 | 0.611                |
| 19      | $\gamma$ | 4 | 4 | 2 | 5 | 3 | 1 | 0.948                |
| 20      | $\gamma$ | 4 | 5 | 3 | 1 | 4 | 2 | 1.042                |
| 21      | $\gamma$ | 5 | 1 | 5 | 4 | 3 | 2 | 0.675                |
The analysis results presented in Table 2 indicate that, according to the calculation range of each influencing factor, the level of influence of each factor affecting pillar stability in underground salt mine can be obtained as follows: Mining depth $H >$ Uniaxial compressive strength $\sigma_c >$ Pillar height $h >$ Pillar width $W_p >$ Room width $W_o >$ Overburden unit weight $\gamma$. The mining depth and uniaxial compressive strength has the largest influence on pillar stability in underground salt mining using the method of strip mining, followed by pillar height and pillar width, whereas room width and overburden unit weight on the pillar stability have relatively small influence.

### 6. Analysis of the relationship between each influencing factor and safety factors of pillar

The relationship between the main factors affecting the stability and safety factors of pillar is presented in Figures 4–9.

![Figure 4](image_url)

**Figure 4.** Relationship between the safety factor of pillar and mining depth.

When the mining depth increases from 240 to 520 m, the pillar safety factor decreases from 2.120 to 0.667. As the mining depth increases, the self-weight stress of the overlying strata increases, as well as the load per unit area of pillars. This leads to a decrease in pillar stability.
Figure 5. Relationship between safety factor of pillar and pillar height

When the pillar height increases from 4 to 12 m, the pillar safety factor decreases from 1.840 to 0.770. As the pillar height increases, the ratio of pillar width to height, the pillar strength converted from the compressive strength of ore and rock, and the stability of pillar decrease.

Figure 6. Relationship between safety factor of pillar and room width.

When the room width increases from 4 to 12 m, the pillar safety factor decreases from 1.706 to 0.877. The roof span is determined by the room width. As the span increases, the roof stress increases, and the stability decreases.
Figure 7. Relationship between safety factor of pillar and pillar width.

When the pillar width increases from 12 to 20 m, the pillar safety factor increases from 0.776 to 1.694. As the pillar width increases, the ratio of pillar width to height, the pillar strength converted from the compressive strength of ore and rock, and the stability of pillar increase.

Figure 8. Relationship between safety factor of pillar and uniaxial compressive strength.

When the uniaxial compressive strength increases from 4 to 12 MPa, the pillar safety factor increases from 0.520 to 1.970. The uniaxial compressive strength of ore and rock directly affects the bearing capacity of pillars. As the uniaxial compressive strength increases, the stability of pillars increases.
Figure 9. Relationship between the pillar safety factor and overburden unit weight.

When the overburden unit weight increases from 1.9 to 2.3 t·m$^{-3}$, the pillar safety factor decreases from 1.661 to 0.897. The bulk density of the overlying strata is primarily affected by the lithology of the related strata. Moreover, it exhibits slight change and relatively low sensitivity. The overburden rocks are primarily composed of Quaternary and Cretaceous systems.

Figures 4–9 show that the pillar safety factor of underground salt mine is negatively related to mining depth, pillar height, room width, and overburden unit weight, i.e., the safety factor decreases as the mining depth, pillar height, room width, and overburden unit weight increase. Moreover, the safety factor of pillar is positively related to pillar width and uniaxial compressive strength, i.e., the safety factor increases as the pillar width and uniaxial compressive strength increase.

Figures 4–9 show the trend of the pillar safety factor of strip mining in underground salt mine, which changes with various influencing factors. It can provide the basis for mining design and optimization of stope structural parameters.

7. Conclusions

As per the calculation formula of the safety factor of pillar in strip mining, the influencing factors of stope stability are analyzed from the aspect of pillar stability. Moreover, the level of influence of each factor on the safety factor of pillar is analyzed using orthogonal range analysis. The following conclusions are drawn:

(1) The primary influencing factors of pillar stability include the mining depth, pillar height, room width, pillar width, uniaxial compressive strength, and unit weight of overlying strata.

(2) According to the range of each influencing factor, the level of influence of each factor on the pillar of the stope are determined as follows: the mining depth and uniaxial compressive strength have the greatest influence on pillar stability, followed by pillar height and pillar width, and the influence of the room width and unit weight of the overlying strata is relatively small.

(3) The safety factor of pillar is negatively correlated with the mining depth, pillar height, room width, and overburden unit weight but positively correlated with pillar width and uniaxial compressive strength.

8. References

[1] LIU Hong-qiang, ZHANG Qin-li, PAN Chang-jia, et al. Analysis of the failure law and stability of the pillar in open stope mining[J]. Journal of Mining and Safety Engineering, 2011, 28(1): 138-143.

[2] C.D. Martina, W.G. Maybee. The strength of hard-rock pillars[J]. International Journal of Rock Mechanics & Mining Sciences, 2000, 37(1): 1239-1246.
[3] Huang Yinghua, Xu Bigen, Tang Shaohui. Study on the Damage patterns and Mechanism of Mined-out Area in Mines using Room-and-Pillar Mining Method[J]. *Mining Research and Development*, 2009, 29(04):24-26.

[4] YAO Gaothui, WU Aixiang, WANG Yi-min, atl. Stability analysis of stope retention pillars in broken rock conditions[J]. *Journal of University of Science and Technology Beijing*, 2011, 33(04):400-405.

[5] Zhang Rengiang, Yu Yeaking, Mu Changping. Analysis of the Sensitiveness of the Stability Influence Factors of Ore Pillars based on Orthogonal Test[J]. *Modern Mining*, 2015, 31(05):11-13.

[6] Hu Bingnan. Pillar stability analysis in strip mining[J]. *Journal of China Coal Society*, 1995(02):205-210.

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

[8] LIU Chang-you, WEI Jan-qing, W AN Zhi-jun, atl. Strata Behaviors and Roof Monitor of Room-and-Pillar System[J]. *Journal of China University of Mining & Technology*, 2002(04):61-64.

[9] LI Jianling. Stope pillar stability and sensitivity analysis of effect factors in overall mining method[J]. *Nonferrous Metals(Mining Section)*, 2010, 62(05):6-8+60.

[10] ZHOU Dong-sheng, YANG Feng-yun. Sensitivity analysis of influencing factors in slope stability analysis based on orthogonal test[J]. *Coal Technology*, 2018, 37(01):147-149.

**Acknowledgments**

This work was supported by a grant from the National Key Research and Development Program (No. 2017YFC0602904).