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Research on rock movement control method in underground mining based on the action of granular lateral pressure

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Abstract: Lateral pressure provided by caving rocks plays an important role in keeping the stability of the sidewall rock mass and controlling the rock movement. Taking Xilinhot Fluorite Mine as an engineering background, we studied the control mechanism of the granular media lateral pressure on the rock movement by combining physical experiments, theoretical analysis and field monitoring. The results indicated that with the increase of the granular media depth, the lateral pressure provided by the static granular media presented two stages of rapid growth and slow growth. The lateral pressure on the footwall was negatively correlated with the dip angle of the orebody, and the lateral pressure on the hanging wall was positively correlated with the dip angle of the orebody. Ore drawing only caused the granular media lateral pressure near the drawing point to decrease. As the granular media moved, the granular media lateral pressure outside the pressure reduction area further increased, and this part of the granular media would play a key role in limiting surface rock movement. On this basis, the improved calculation formula of GLMP was given, which could be better applied to calculate the GLMP and critical granular media column with different dip angles. The action mechanism of the GLMP in the control of the surface rock movement was clarified. The granular body in the collapse pit was mainly composed of three parts: the bottom loose granular media column, the middle compaction granular media column and the upper critical granular media column. The critical granular media column was the most important area to control surface subsidence and rock movement. Finally, through field practice, after effective filling of the collapse pit, the surface vertical displacement of the hanging wall and footwall was decreased by 56.8% and 55.6%, respectively, and the control effect of surface rock movement was remarkable.

Keywords: lateral pressure physical experiment critical granular media column rock movement control underground mining

1 Introduction

Underground non-coal mines are usually mined by caving method or empty field method (Heidarzadeh et al. 2019; Liu et al. 2021; Xia et al. 2021; Xu et al. 2021; Castro et al. 2022). When the span of the goaf exceeds the critical caving span with the continuous mining (He et al. 2017; Ren et al. 2018), the roof rock mass of the goaf will cave. After the caving develops to the surface, it will lead to surface rock movement and large subsidence pits. If the subsidence range is not effectively controlled, it will pose a serious threat to the surface environment, industrial and operators (Woo et al. 2013; Song et al. 2018; Hu et al. 2017). The development of collapse and rock movement range depends on the break form and structural plane distribution of the surrounding rock (Huang et al. 2010; Feng et al. 2019; Feng et al. 2021). On the other hand, it depends on the lateral pressure support of caving and filling granular media. Engineering practice shows that the implementation of granular filling in the underground stope can effectively control the roof caving and surface rock movement(Zhang et al. 2015; Li et al. 2014; Raffaldi et al. 2019). Therefore, it is necessary to study the support mechanism of the granular media to the surrounding

rock, and achieve effective predict and control of surface collapse and rock movement (Li et al. 2012; Ren et al. 2018; Li et al. 2016).

In recent years, researchers have carried out extensive research on granular lateral pressure (Mirmoazen et al. 2021; Kazempour S et al. 2021; Chen et al. 2019; Xie et al. 2019; Kamiloglu et al. 2017). He et al. (2021) proposed the backfilling of the granular rock into the collapse pit can prevent the surface strata movement. Kobyłka et al. (2017) proposed when opening a discharge gate may result in a sudden increase in the lateral pressure with a simultaneous ramp down of vertical pressure. Li et al. (2022) explored the influences of the compressive deformation of backfill materials on the strata movement and stress evolution in deep backfill mining, and pointed out that the lower the compression ratio of backfill materials, the better the control of overlying strata. Li et al. (2017) pointed out that the lateral pressure of confined granular material will be influenced by both the wall movement and the confined material width. Li et al. (2019) pointed out that a reasonable particle size distribution can significantly improve stress characteristics, reduce crushing of particles in the samples, and increase the stiffness of the samples, so as to achieve better compaction effects. Le et al. (2022) proposed a constitutive model that takes the real physical characteristics of granular material into account was proposed with variable deformation modulus, and the effects of the particle size of the granular backfill and the height and buried depth of mined-out stopes on surface subsidence have been clarified. Xu et al. (2021) used the discrete element method (DEM) to study the lateral earth pressure change of granular materials under lateral strain-controlled cyclic loading, and a unique relationship is revealed between the deviator stress ratio and the deviator fabric of strong contacts on the micro-scale.These studies all have a common understanding the lateral pressure provided by granular media can play a certain supporting role and can be applied to the rock movement control in the mining.

The waste rock produced by mining has the characteristics of non-uniformity. With the progress of underground mining, the granular media of the overburden is constantly moving, which leads to a more complex interaction between loose blocks, and cannot be displayed intuitively. At the same time, reasons such as particle size distribution, underground ore drawing and ore body inclination will have an impact on the lateral pressure of the granular media(Liu et al. 2020), and there are few research reports on this aspect. In this paper, these reasons are considered, and the lateral pressure distribution characteristics of the granular media in both static and flowing states are obtained through similar physical experiments. An improved calculation formula of the granular media lateral pressure was obtained, the mechanism of the granular media lateral pressure was clarified, and it was successfully applied to the control of surface rock movement in Xilinhot Fluorite Mine. This work helps researchers to better understand the mechanism of the granular media lateral pressure, and has certain guiding significance for the effective control of ground subsidence and rock movement caused by underground mining.

2. Analysis of the supporting effect of the granular media on the surrounding rock

If the ore-rock contact surface of the collapsed pit is broken and there is no granular media support, the broken rock mass will be upright and fragmented along the ore-rock contact surface. When the granular media in the pit is high, the surrounding rock of the sidewall is stable, and the surrounding rock on the other side is intensified because of the lack of granular media support (Fig. 1).

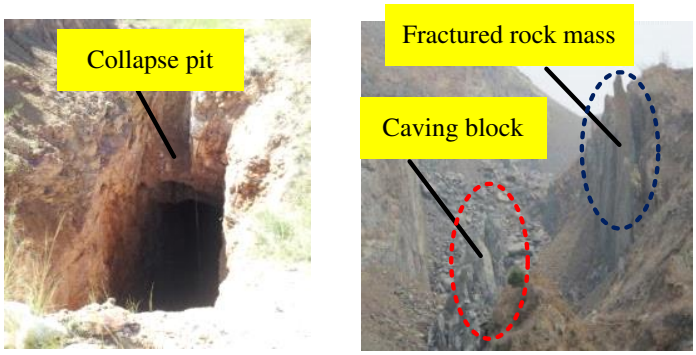


Fig.1 Surface collapse pits

By analyzing the failure process of the surrounding rock on the sidewall of the collapse pit, when the caving granular media in the collapsed pit moves downward, the lateral support force exerted by the top granular media on the sidewall will unload. Under the combined influence of reasons such as stress, self-weight stress and structural plane, cracks are formed along the structural plane toward the collapse pit. The sidewall rock will become unstable as the cracks expand, causing the surrounding rock to collapse or slip damage. Lateral caving and framing of the rock mass will lead to the continuous expansion of the subsidence pit. If the buckling block is supported by the lateral support of the granular media, the fractured block will be stable (Fig. 2).

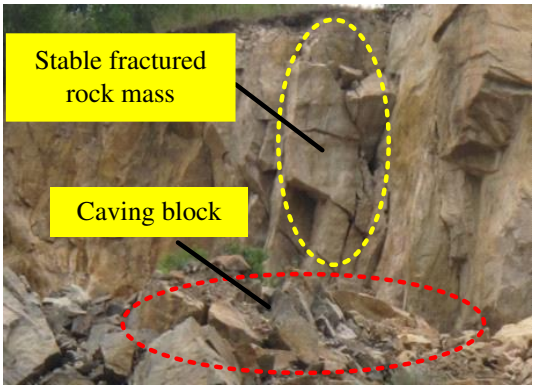


Fig.2 Control of the granular media to the fractured rocks of the sidewall

3 Experimental analysis of the granular media lateral pressure

3.1 Experimental model and materials

In this paper, the granular media lateral pressure is abbreviated as “GMLP”. The research adopts the lateral pressure experimental to study the variation law of the GLMP. The size of the model is l50cm×20cm×160cm (length×width×height), the model similarity ratio is 1:100, and there are 16 CSF-1A sensor acquisition channels on both sides. The top of the experimental device is provided with a granular media inlet, and four granular media drawing ports are set at the bottom of the device, with a size of 3cm × 3cm. The data is displayed on the computer in two ways: the curve view and the data view (Fig. 3). The experiment is based on the particle size distribution of the waste rock powder in Xilinhot Fluorite Mine, and dolomite is used as the experimental granular media. The gradation of experimental granular is shown in Table 1.

Table 1 Gradation of experimental granular

granularity（cm）	＜0.1	0.1～0.3	0.30～0.7	0.70～1	＞1
gradation（%）	8.6	28.3	45.9	11.5	5.7

The experiment selected three groups of ore body dip angles of 80°, 85° and 90°. The single discharge of the granular media was about 1 kg. During the discharge, the released granular media should be backfilled into the model in time to ensure the height of the granular media did not change significantly. In the experiment, the side away from the outlet was the upper plate, and the side near the outlet was the lower plate.

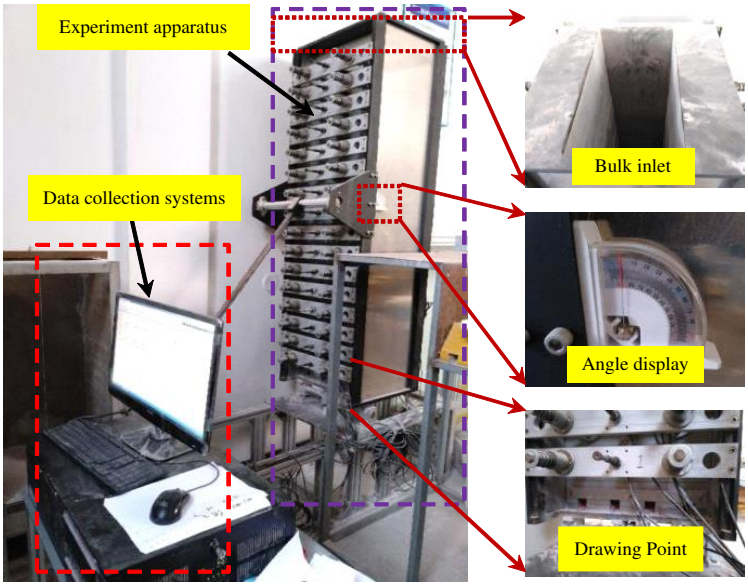
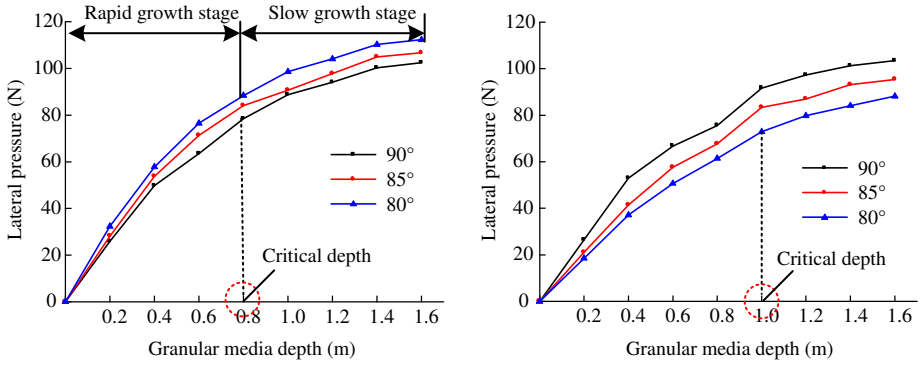


Fig.3 Granular lateral pressure experimental equipment

3.2 Analysis of experimental results

(1) Experimental results of the GLMP

The overall performance of the granular media side pressure was a monotonous increase, which was mainly divided into two stages: the fast growth stage and the slow growth stage. As the granular media height increased, the lateral pressure of the granular media increased rapidly at first. When the contact area between the granular media gradually became saturated and solid, the strong interaction between the granular media weakened, causing the lateral pressure to change gradually from a rapid increase to a slow increase, and gradually stabilized (Fig. 4).



(a) Lateral pressure on the footwall (b) Lateral pressure on the hanging wall

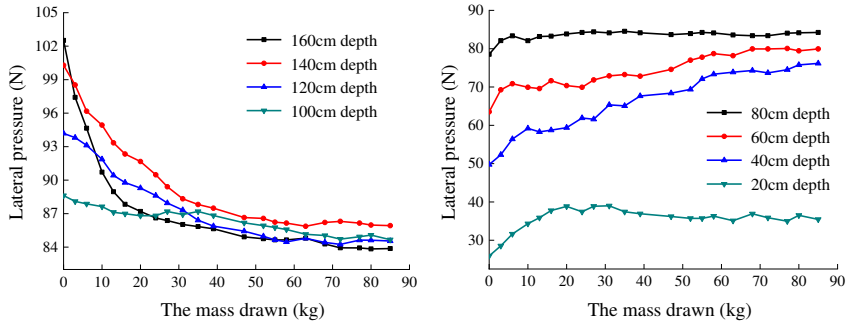
Fig.4 GLMP curves affected by the granular height under different inclination angles

The study found that with the increase of the dip angle, the pressure value of the footwall gradually decreased, and the average decrease rate was about 4.5%, and the critical depth was about 0.8m. The pressure on the hanging wall gradually increased, and the average increase rate was about 7.9%, the depth was about 1.0m. It showed the lateral pressure of the granular media on the footwall was more likely to be stable. With the change of the dip angle, the pressure value of

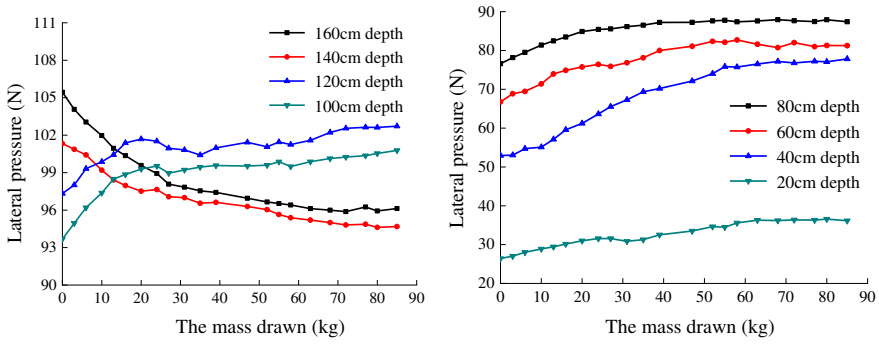
the footwall was correlated negatively with the dip angle, and the pressure value of the hanging wall was correlated positively with the dip angle. The variation range of the GLMP on the hanging wall was higher than that of the footwall. The effect of the GLMP on the hanging wall was more prominent.

(2) Experimental results of the GLMP

The GLMP curve under the condition of 90° inclination was shown in Fig. 5. With the release and backfilling of the granular media, the GLMP with a depth of 160cm~100cm on the footwall decreased. When the amount of granular media released reached about 50kg, the lateral pressure changed smoothly. The GLMP with a depth of 80cm increased slowly and then changed steadily, indicating the granular media had met the critical depth. The GLMP with a depth of 40cm and 60cm gradually increased, indicating the granular media at this position would not move significantly with the release of the bottom granular media. The critical granular media column existed in the granular media above this position. The lateral pressure at the depth of 160cm and 140cm on the hanging wall gradually decreased. The variation trend of the lateral pressure at the depth of 120cm and 100cm could be divided into four processes. When the released granular media was 0~20kg, the lateral pressure increased rapidly and reached a peak value. When the released granular media was 20~35kg, the GLMP decreased and then rebounded, When the released granular media was 35~60kg, the GLMP changed smoothly. When the released granular media was 60~85kg, the GLMP increased slowly. It showed the loose range of the granular media was at the depth of 140 cm. The decrease of the GLMP after reaching the peak value might be related to the arching between the granular media. After the arch failed, the granular media moved down rapidly to fill the bottom space, resulting in a decrease of the GLMP.



(a) Lateral pressure on the footwall

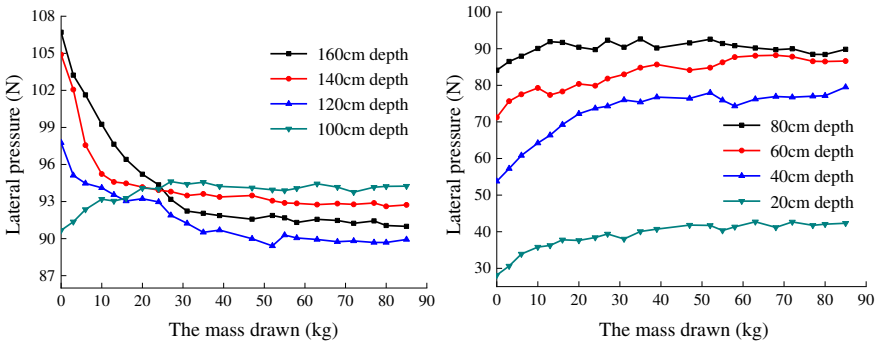


(b) Lateral pressure on the hanging wall

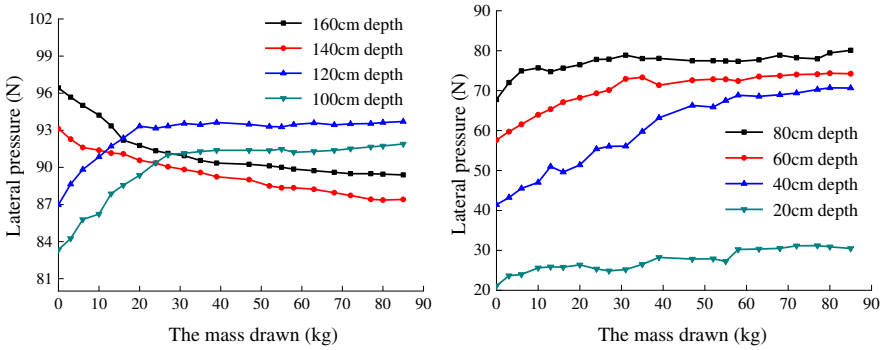
Fig.5 The GLMP curve under the condition of 90° inclination

The GLMP curve under the condition of 85° inclination was shown in Fig. 6. On the

footwall, the GLMP decreased with a depth of 160cm~120cm, and the average decrease rates were 14.17%, 10.87%, and 7.23%, respectively. Different from the 90° inclination angle, the GLMP with a depth of 100cm began to increase, and the average increase rate reached 2.96%, showing the loose range was at the depth of 120cm. On the hanging wall, the variation trend of the GLMP with the depth of 160cm~100cm was the same as that of the 90° inclination angle. The average decrease rate of the GLMP with the depth of 160cm and 140cm was 6.54% and 4.07%, respectively. The average increase rates of the GLMP and the depth of 120cm and 100cm were 5.72% and 8.56%, respectively.



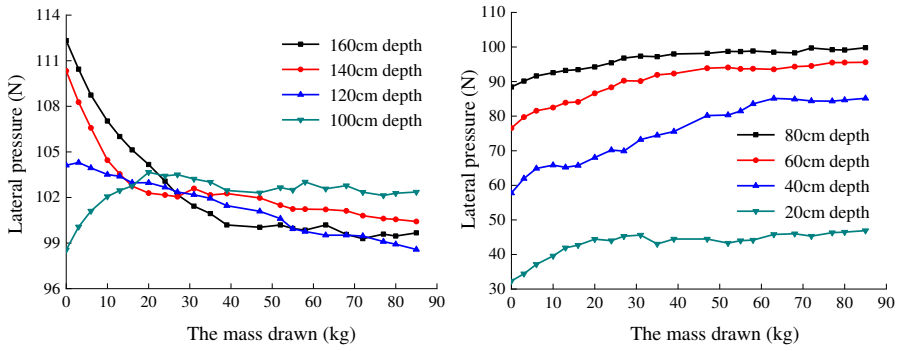
(a) Lateral pressure on the footwall



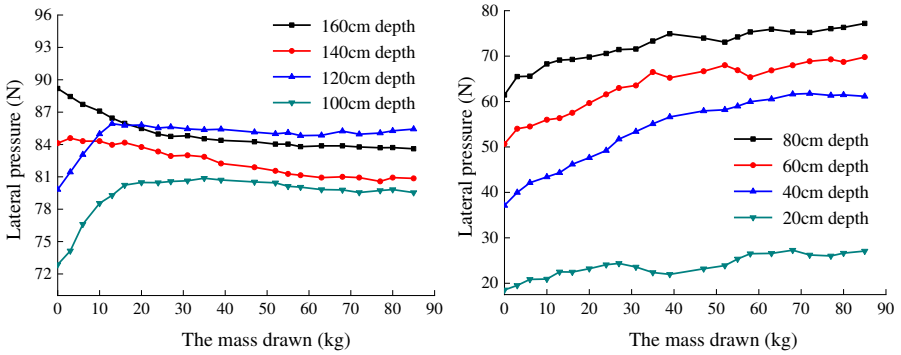
(b) Lateral pressure on the hanging wall

Fig.6 The GLMP curve under the condition of 85° inclination

The GLMP curve under the condition of 80° inclination was shown in Fig. 7. On the footwall, the GLMP with a depth of 160cm~120cm decreased, with an average decrease rate of 10.93%, 7.50%, and 4.01%, respectively. The average increase rate of the GLMP with a depth of 100cm was 4.36%. The loose range was at the depth of 100cm. The variation trend of the GLMP at the depth of 80cm-20cm was the same as that of the 85° inclination angle. On the hanging wall, the variation trend of the GLMP with a depth of 160cm~120cm was the same as that of the 85° inclination angle. The average increase rates of the GLMP were 6.96% and 6.47%, respectively.



(a) Lateral pressure on the footwall



(b) Lateral pressure on the hanging wall

Fig.7 The GLMP curve under the condition of 80° inclination

Research shows that under the condition of keeping the height of the granular media constant, during releasing the granular media, only the GLMP near the ore drawing port reduce. The granular media near the ore drawing point moves from the hanging wall to the footwall, resulting in the loose range of the granular media on the hanging wall is higher than that on the footwall. If the height remains unchanged, the underground ore drawing will not affect the stability of the surrounding rock of the collapsed pit. With the granular media moving, the GLMP will increase outside the pressure decrease zone, and this part of the granular media will play a key role in restricting the near-surface rock movement.

4 Construction of the mechanical model of the GLMP

According to the expansion research of the Janssen GLMP theory (Chen 2010), the calculation formula of the GLMP is expressed as follows:

$$P=\frac{\gamma\cdot S}{\mu\cdot l}\cdot\sin\alpha\cdot\left(1-\frac{\mu}{\tan\alpha}\right)\cdot\left[1-\exp(-\frac{\mu\cdot k_w\cdot l}{S\cdot\sin\alpha}\cdot h)\right] \quad (1)$$

Where γ is density of the granular media, kN m^{-3}; S is horizontal projected area of the granular media, m^2; α is inclination angle of the ore body, °; l is horizontal projected perimeter of the granular media, m; k_w is GLMP coefficient; μ is friction coefficient between the granular media and the sidewall; μ=tanδ, δ is friction angle between the granular media and the sidewall, °; h is depth of the granular media, m.

According to formula (1), it can be seen the GLMP is affected by various reasons, and the mechanical analysis model is established based on the interaction between the granular media and the sidewall of the collapsed pit (Fig. 8). In Fig. 8, *OA* and *BC* are upper and lower boundaries of the wall, α is inclination angle of the wall (ore body). *OAC* section is taken as the analysis object in the study, *AC* section is the slip surface between the granular media, and β is angle of the slip

plane and the horizontal plane.

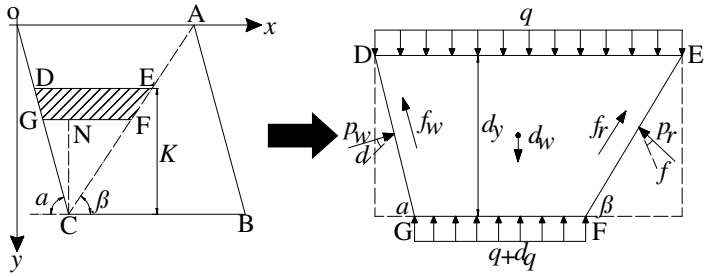


Fig.8 The mechanics model of the granular media lateral pressure

DEFG at a certain depth is taken from the *OAC* section for mechanical analysis. The thickness is dy, the vertical load acting on the top is q, the bottom load is $q+dq$, and the lateral load acting on the wall is p_w. The friction force between the wall and the granular media is f_w, and the friction angle between the wall and the granular media is δ. The reaction force of the granular media on the slip surface is P_r, and the friction angle in the granular media is φ. The friction angle between the granular media is φ, the friction force is f_r, and the unit body weight is d_w.

According to the relationship in Fig. 8, it can be obtained:

$$DG = \frac{d_y}{\sin\alpha} \tag{2}$$

$$EF = \frac{d_y}{\sin\beta} \tag{3}$$

$$L_1 = \cot\alpha \cdot d_y \tag{4}$$

$$L_2 = \cot\beta \cdot d_y \tag{5}$$

$$FG = NG + NF = (K - d_y)(\cot\alpha + \cot\beta) \tag{6}$$

$$DE = L_1 + L_2 + FG = K(\cot\alpha + \cot\beta) \tag{7}$$

The friction between the wall and the granular media is expressed as follows:

$$f_w = P_w \tan\delta \tag{8}$$

The frictional force between dispersions is expressed as follows:

$$f_\gamma = P_\gamma \tan\varphi \tag{9}$$

According to the balance of the force in the horizontal direction, the expression is as follows:

$$P_w \sin\alpha \cdot DG - f_w \cos\alpha \cdot DG - P_r \sin\beta \cdot EF + f_r \cos\beta \cdot EF = 0 \tag{10}$$

Substituting formulas (2), (3), (8), and (9) into formula (10), the following expression is obtained by simplification:

$$\frac{P_r}{P_w} = \frac{1 - \tan\delta\cot\alpha}{1 - \tan\varphi\cot\beta} \tag{11}$$

According to the balance of the force in the vertical direction, the expression is as follows:

$$P_w \cos\alpha \cdot DG + f_w \sin\alpha \cdot DG + (q + d_q) \cdot FG - q \cdot DE + P_r \cos\beta \cdot EF + f_r \sin\beta \cdot EF - d_w \cdot FG = 0 \tag{12}$$

Assuming the dispersion is not cohesive, the expression is as follows:

$$P_w = k_w \cdot q \tag{13}$$

Where k_w is coefficient of the GLMP.

Substituting formulas (2), (3), (6), (7), (8), (9), (13) into (12), omitting the second-order parameters, the following expression is obtained:

$$K \cdot \frac{d_q}{d_y} = \tau + q \cdot (1 - \frac{k_w(\cot\alpha + \tan\delta)}{\cot\alpha + \cot\beta} - \frac{k_w(\cot\beta + \tan\varphi)}{(\cot\alpha + \cot\beta)} \cdot \frac{P_r}{P_w}) \tag{14}$$

Taking the center point Q of the slip surface between the granular media as the moment center, according to the moment balance condition, the expression is as follows:

$$q \cdot DE \cdot (\frac{DE}{2} - \frac{L_2}{2}) - f_w \sin\alpha \cdot DG \cdot (FG + \frac{L_1}{2} + \frac{L_2}{2}) - (q + d_q) \cdot FG \cdot (\frac{FG}{2} + \frac{L_2}{2}) + \frac{d_w}{2} \cdot (FG + \frac{L_1}{2} + \frac{L_2}{2}) - P_w \cdot \cot\alpha \cdot d_y \cdot (FG + \frac{L_1}{2} + \frac{L_2}{2}) = 0 \tag{15}$$

Substituting formulas (2), (3), (4), (5), (6), (7), (8), (13) into formula (15), omitting the second-order parameters, the following expression is obtained:

$$K \cdot \frac{d_q}{d_y} = \tau + q \cdot \frac{1 - k_w}{2 + \cot\beta / \cot\alpha} \tag{16}$$

Combining formula (14) and formula (16), the expression is as follows:

$$1 - \frac{k_w(\cot\alpha + \tan\delta)}{\cot\alpha + \cot\beta} - \frac{k_w(\cot\beta + \tan\varphi)}{(\cot\alpha + \cot\beta)} \cdot \frac{P_r}{P_w} = \frac{1 - k_w}{2 + \cot\beta / \cot\alpha} \tag{17}$$

Finally, the coefficient of the GLMP is expressed as follows:

$$k_w = \frac{\cot\alpha + \cot\beta}{\left(\frac{\cot\alpha + \tan\delta}{\cot\alpha + \cot\beta} + \frac{\cot\beta + \tan\varphi}{\cot\alpha + \cot\beta} \cdot \frac{1 - \tan\varphi\cot\beta}{1 - \tan\delta\cot\alpha}\right) \cdot \left(2\cot\alpha + \cot\beta\right) - \cot\alpha} \tag{18}$$

In the Xilinhot Fluorite Mine, the friction angle between the granular media and the wall is 9°, the friction angle in the granular media is 25°. The ore body dip angle varies from 80° to 90°, and the angle between the slip plane and the horizontal plane is β=48 °. We bring these parameters into equation (18), the GLMP coefficient under different dip angles can be solved. Where the GLMP coefficient of the 80° ore body dip angle is put into formula (1), the comparison between the theoretical value and the experimental value of the GLMP is shown in Fig. 9.

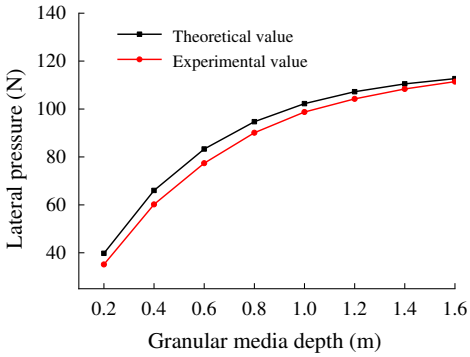


Fig.9 Comparison of theoretical and experimental values of the GLMP

The calculated GLMP based on the theoretically is consistent with the experimental value basically, which verifies the reliability of the theoretically obtained GLMP.

Liu et al. (2018) combined theoretical analysis with experiments, and gave a formula for determining the height of the critical granular media column based on the GLMP:

$$H_0 = H_3 - \frac{S}{\mu k_w l} \cdot \ln \frac{\gamma S}{\gamma S - \mu P_{max} l} \tag{19}$$

$$H_3 = H_2 - H_4 \tag{20}$$

Where H_3 is height of the dense granular media column, m; H_2 is total height of the granular media, m; H_4 is height of the loose granular media column, m; P_{max} is maximum value of the GLMP when it reaches a steady state under the influence of ore drawing.

According to the research of ore drawing theory, the height of the loose body is about 2.5 times of the caving height of the overburden [24], the calculation formula of the caving height of the overburden is as follows:

$$h_a = h_b - h_c - L \cdot (\xi - 1) \tag{21}$$

Where h_b is height of the ore house, m; h_c is height of the residual ore after the ore drawing, m; L is thickness of the top pillar, m; ξ is fragmentation coefficient.

Take Xilinhot Fluorite Mine and Gongchangling Iron Mine as examples. In the Xilinhot Fluorite Mine, h_b=26m, h_c=1.5m, ξ=1.5, L=14m, γ=3.18×10^3 kg/m^3. In the Gongchangling Iron Mine, h_b=45m, h_c=2m, ξ=1.5, L=15m, γ=4.1×10^3 kg/m^3. Substitute the relevant parameters into formula (21), we can get the drop heights of the overburden in two mines are 17.5m and 35.5m, respectively, determine the heights of the loose body are 43.75m and 88.75m, respectively.

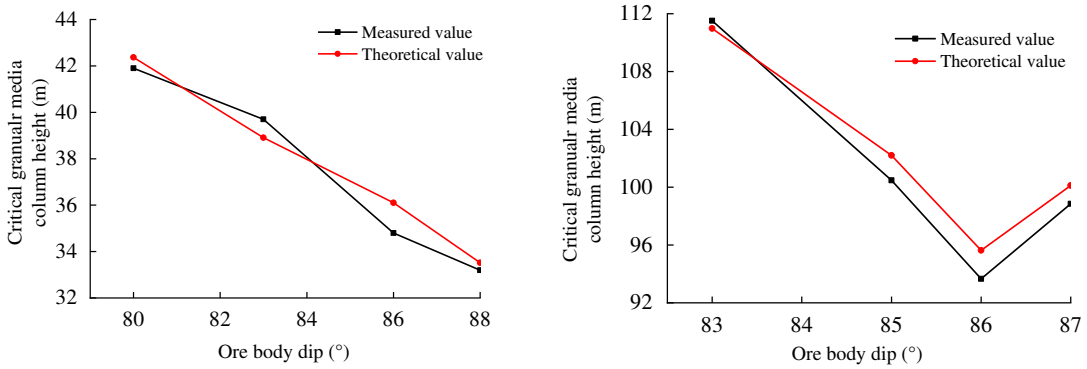
According to the experimental results of the GLMP in Fig. 7, the GLMP increases significantly and stably with a depth of 1.2m. Based on the experimental value, the theoretical formula (1) is revised. Taking $l \cdot h / S$ as a dimensionless variable, we set the correction coefficients R_1, R_2, R_3, the formula (1) is organized as:

$$P_{max} = R_1 \frac{\gamma S}{\mu l} \sin\alpha \cdot \left(1 - \frac{\mu}{\tan\alpha}\right)^{R_2} \cdot \left[1 - R_3 \exp\left(-\frac{\mu k_w l}{\sin\alpha S} H_3\right)\right] \tag{22}$$

The GLMP at 1.2m depth in the lateral pressure experiment with different inclination angles are put into formula (22), and analyzed by Matlab software to get the correction coefficients R_1=0.5, R_2 =8.15, R_3=-1.95. The improved calculation formula of the GLMP is expressed as follows:

$$P_{\max}=0.5\times\frac{\gamma S}{\mu l}\sin\alpha\cdot\left(1-\frac{\mu}{\tan\alpha}\right)^{8.15}\cdot\left[1+1.95\exp(-\frac{\mu k_w l}{\sin\alpha S}H_3)\right] \tag{23}$$

Substituting parameters into formulas (18), (23) and (19), the comparison between the theoretically value and the field measured value of the critical granular media column height in two mines is shown in Fig. 10.



(a) Xilinhot Fluorite Mine (b) Gongchangling Iron Mine

Fig.10 Comparison of theoretical and measured values of the critical granular medium column

It can be seen from Fig. 10, the theoretical value of the critical granular media column height obtained according to the improved calculation formula is close to the field measured value relatively. The improved GLMP calculation formula can be better applied to engineering.

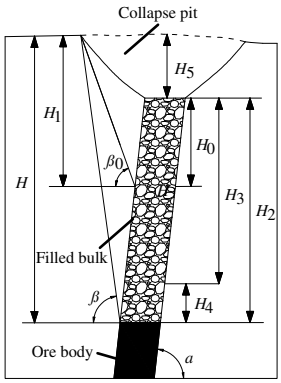


Fig.11 Determination method of granular media column

According to the theoretical research of the critical granular media column (Zhang et al. 2019; Zheng et al. 2014), the boundary of the surface collapse area extends downward to the boundary of the ore body. The granular media column above this position is the critical granular media column (Fig.11). The relationship between the slump angle and the critical depth is as follows:

$$H_1=\frac{H\cdot(\tan\beta\cdot\cot\alpha)}{\tan\beta\cdot(\cot\alpha+\cot\beta_0)} \tag{24}$$

Where H is the mining depth, m; β is the slump angle, °; β_0 is the rock displacement angle, °; α is the ore body dip angle, °.

Combining formula (19) and (24), the maximum allowable unfilled height of the collapse pit under the effective control of collapse and rock movement is obtained as follows:

$$H_5=H_1\text{-}H_0 \tag{25}$$

Through the research, this formula can be used to fill mine collapse pits, which can achieve effective control of surface collapse and rock movement.

5. Surface rock movement control mechanism

Based on the experimental results of the GLMP, the granular media near the drawing point first loosens, and the compaction density of the loose body gradually decreases, resulting in the GLMP on the surrounding rock decreases. After the end of the ore drawing, the flow trend of the loose body near the ore drawing port from the hanging wall to the footwall slows down. Finally, the hanging wall loose body slow down and solidify, the final movement trace of the granular media is parallel to the wall of the surrounding rock (Fig. 12). When the backfilling granular media provides enough lateral support force, the surrounding rock of the collapse pit will no longer be fragmented, and the surface collapse and rock movement expansion will be controlled.

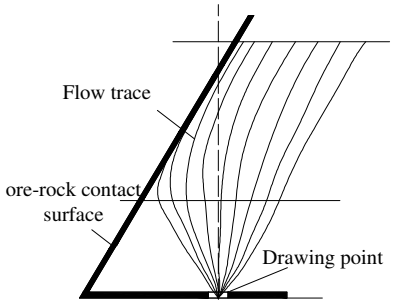


Fig.12 Granular flow pattern under the ore drawing

The GLMP largely depends on the density of the granular media, and the density of the granular media depends on the granular media height. With the increase of the granular media height, the granular media actively exerts a lateral pressure σ_1 on the sidewall. At the same time, it is affected by the deformation of surrounding rocks, the granular media squeeze each other, resulting in a decrease in porosity and an increase in the number of contact points. The strong interaction between particles will bear the lateral pressure σ_2 exerted by the sidewall rock mass (Fig. 13). The loose area at the bottom is mainly affected by the lateral pressure σ_1, and the upper dense area is jointly affected by the lateral pressure $\sigma 1$ and σ_2, which provides support for the effective action of the upper critical granular media column.

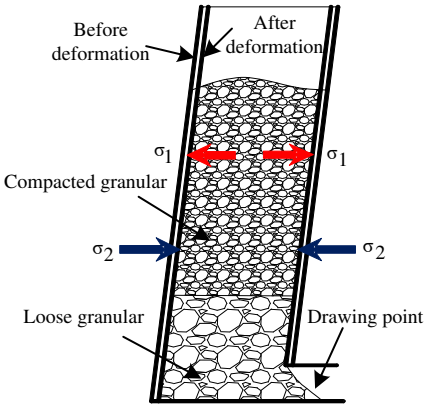


Fig.13 The relationship between the GLMP and the surrounding rock

Comprehensive analysis shows the granular media in the collapse pit are mainly divided into three action regions: the loose granular media column, the compacted granular media column and the critical granular media column (Fig. 14). The change of the lateral pressure of the loose body

in the action area of the loose granular media column will not affect the surface collapse and rock movement. In the action area of the compacted granular media column, the granular media always keeps a high-density compacted state. The GLMP will increase until it tends to be stable, providing stress support for the upper critical granular media column. The critical granular media column is the most important area to control surface collapse and rock movement, and it provides lateral support. The lateral support force it provides can keep the rock mass stable within a certain height above the critical granular media column, to control the surface collapse and rock movement.

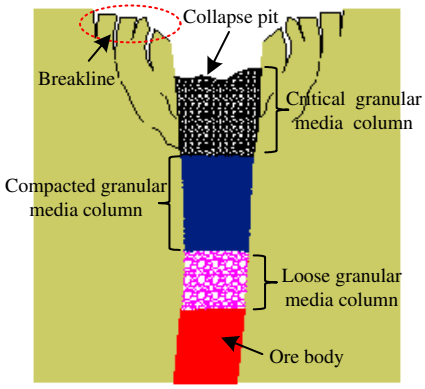


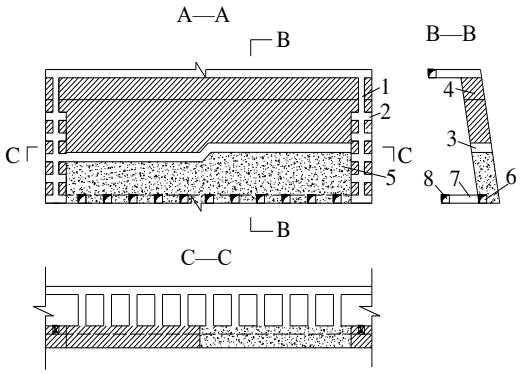
Fig.14 Distribution of the granular media column in the collapse pit

6. Control effect of rock movement

6.1 Engineering background

The Xilinhot Fluorite Mine belongs to China Iron and Steel Group Mining Company and is located in Xilinhot City, Inner Mongolia Autonomous Region, northwest China. The wall rock of ore-rock contact zone is mainly altered diorite, with 0.6 m~1.2 m alteration, and the stability is poor. The wall rock near ore is mainly biotite plagioclase granite.

The fluorite grade is between 20.05 % and 96.20 %, with an average of 63.21 %. The orebody intendancy ranging from 100° to 105°, the dip angle ranging from 80°to 90°, the horizontal thickness ranging from 4 m to 12 m, average thickness is 7 m, the elevation is 480m. The thickness and occurrence of the ore body are stable, and the mine adopts shaft development and high-end wall sublevel caving mining. The stage height is 40 m, the sublevel height is 20 m, and the caving step is 1.6 m. The mining roadways are arranged along the vein, and the mining route is close to the footwall of the ore body. The ore recovery rate is 82.01 %, and the dilution rate is 17.89 %. The stope structure is shown in Fig. 15.



1-ventilated riser；2-contact roadway；3- Workspace；4- top pillar；5- ore pile；

6-bottom roadway；7- across vein roadway；8- haulage roadway

Fig. 15 The stope structure of the short-hole shrinkage method

6.2 Surface collapse and rock movement control methods

Taking Xilinhot Fluorite Mine as an example, because of the influence of the short-hole shrinkage method, an obvious collapse pit was formed on the surface. The dip angle of the collapse pit is 86°. According to Figure 10(a), the critical granular media column height of the collapse pit is 35m. The mining depth of this mine is 225m, the slump angle is 83°, and the rock movement angle is 65°. Substituting the relevant parameters into formulas (24) and (25), the maximum allowable unfilled height of the collapse pit is calculated as 2.5m. Subsequently, the collapse pit was fully filled with waste rock extracted from the shaft until the filling height requirements were met. The surface was covered with soil, and the soil height was 2.5m.

In order to verify the effect of surface rock movement control, the change characteristics of the surface subsidence before and after the collapse pit filling were monitored. The layout of the monitoring points was shown in Fig.16. The monitoring points were arranged perpendicular to the strike of the ore body. 8 monitoring points were arranged on the hanging wall and footwall of the collapse pit, with four monitoring points on each side, and the average distance between the monitoring points was 4m. The total station was used for monitoring, and the monitoring period was once every half month, the monitoring period was about 3 months.

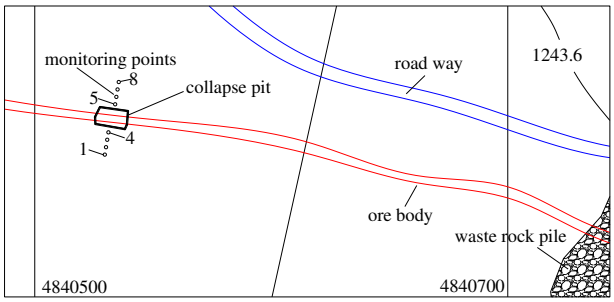
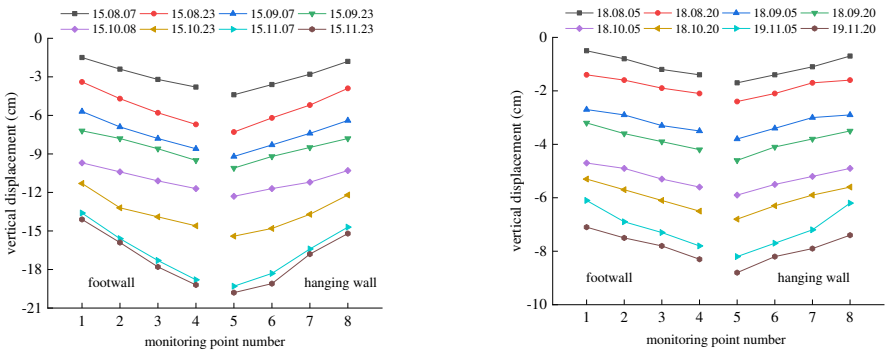


Fig 16 Layout of surface rock movement monitoring points

The monitoring results are shown in Fig. 17. As the distance between the monitoring point and the collapse pit decreased, the vertical displacement showed an overall increasing trend, and the vertical displacement of the hanging wall was higher than that of the footwall. When the collapse pit was not filled, the maximum vertical displacement of monitoring points 4# and 5# near the collapse pit was 19.2cm and 19.8cm, respectively. After the collapse pit was filled, the maximum vertical displacement of monitoring points 4# and 5# near the collapse pit was 8.3 cm and 8.8 cm, respectively. The vertical displacement decreased by 56.8% and 55.6, respectively.



(a) Before filling the collapse pit (b) After filling the collapse pit

Fig. 17 Monitoring results of surface rock movement

After nearly a year of observation, a fracture line appeared on the hanging wall of the collapsed pit (Fig. 18), which was caused by the slight dislocation of the granular media during the settling process, and the surface did not change significantly after compaction. Therefore, the control method of surface rock movement based on the GLMP has achieved good control effect in field application.

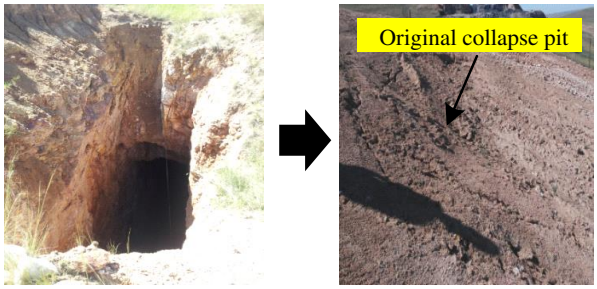


Fig. 18 Comparison of collapse pit before and after filling

7 Conclusions

(1) Through the experimental study of the GLMP, the static GLMP shows two stages of rapid growth and slow growth with the increase of the depth. The lateral pressure on the hanging wall is smaller than the footwall. The influence of the GLMP on the hanging wall rock mass is more prominent. When the granular media filling height remains unchanged, the ore drawing only causes the GLMP near the drawing port to decrease, and the decrease range is less than or approximately equal to the critical depth value. The GLMP outside the lowering zone is not affected by the ore drawing.

(2) The research gives an improved calculation formula for the GLMP. By comparing with the experimental and field measured data, the theoretical calculation formula can be well applied to calculate and analyze the GLMP and the height of the critical granular media column under different ore body conditions.

(3) Under the influence of ore drawing, the granular media in the collapse pit are mainly divided into three action zones: loose granular media column, compacted granular media column and critical granular media column. The change of the GLMP in the action area of the loose granular media column will not affect the surface collapse and rock movement. The lateral support force provided by the granular media in the critical granular media column action area is the key reason affecting the rock movement. If the critical granular media column height requirements are met, the surface collapse and rock movement will be controlled.

(4) Through surface rock movement monitoring, as the distance from the sidewall of the collapse pit decreases, the vertical displacement shows an overall increasing trend. The vertical displacement on the hanging wall is higher. The height of the critical granular media column in the collapse pit is 35m, and the maximum allowable unfilled height of the surface is 2.5m, which can guide the effective filling of the collapse pit.

(5) Through field practice, after effective filling of the collapse pit, a small fracture line appeared on the hanging wall because of the slight dislocation of the granular media in the collapse pit, and the overall stability was good. Compared with the collapsed pit without filling, the vertical displacements of the hanging wall and the footwall were reduced by 56.8% and 55.6%, respectively. This method realizes the effective control of the surface collapse and rock movement

of the Xilinhot Fluorite Mine.

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