Analysis of migration and failure regular pattern of overlying strata in different mining heights

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Abstract. In this paper, the H-mine is taken as the research background, and the critical layer theory is used to determine the reasonable height of the “three belts” of the overlying strata in different mining heights. This thesis uses FLAC3d numerical simulation to analyze the law of failure in roof movement under different mining height conditions. The research shows that the height of the fracture zone increases abruptly with the increase of the mining height due to the influence of the key layer. Each mutation indicates that a key layer is broken to form the masonry beam structure. In the numerical simulation, the plastic zone of the working face has a "saddle-shaped" distribution with high ends and low middle. With the increase of mining height, the differences between the plastic zone range above the mining boundary and the central plastic zone is reduced. From the bottom to the top, the roof is divided into several regions, that is, tensile failure region, the shear tension failure region, shear failure zones and undamaged areas. With the increase of mining height, the pre-stress concentration factor and the lateral stress concentration coefficient increase linearly, and the lateral stress concentration factor is slightly lower than the pre-stress concentration factor. The peak position increases as the height increases.

1. Engineering background
H-mine has large ground pressure, soft and fractured surrounding rock and developed joints. Due to the combined effects of ground pressure, tectonic stress and mining stress, the roadway is seriously damaged, which directly threatens the safe production of the mine. 7 coal is 1~2.5m thick, and 8 coal is 6~8m thick coal seam. The conventional downward mining sequence is adopted, but the initial output is low, and the economic benefit will be poor. After the lower coal seam is mined, the stress balance state of the original rock is destroyed. The overlying rock strata suspended in the goaf loses effective stress support, causing the surrounding rock to move and deform to the goaf under the action of stress, causing the collapse and fall of roof, and the rock stratum. The movement of the goaf direction will inevitably cause lateral and longitudinal deformation and damage of the overburden. These phenomena are related to the mining of the lower coal seam and the integrity of the interlayer rock. However, due to the increase of mining height, with the increase of the mining space of large mining height stope, the height of caving
zone increases accordingly and it can be formed in the common mining height. The key layer that stabilizes the "masonry beam" structure will also enter the slump zone and form a stable structure at a higher horizon [1-5]. The surrounding rock stress field and the expansion and development of the fault zone will inevitably change, but few scholars have studied the law of overburden migration under different mining height conditions [6]. Therefore, this paper takes H-mine as the engineering background, and uses the key layer theory to determine the reasonable height of the “three belts” of overlying strata in different mining heights. The FLAC3d numerical simulation is used to analyze the roof movement and failure law under different mining heights.

The average depth of 8 coal is 530m between 520m and 540m. There is no gas geological data in the mining area. According to the research of H-mine 8 coal seam outburst risk prediction, the north wing of the minefield is determined to be a gas weathering zone with a gas content lower than the 550m elevation. 8 Coal is mainly affected by sandstone fissure water, and the local section is affected by igneous rock erosion. The normal water inflow is expected to be 0~3.0m$^3$/h, and the maximum water inflow is 10m$^3$/h. The amount of water may increase near the fault or at the development of the fracture.

2. Application of Critical Layer Theory to Determine the Reasonable “Three Zones” Height
Because the overlying soft rock of the key stratum moves harmoniously with the key stratum, when the key stratum breaks, the overlying soft rock will also produce the same breaking form as the key stratum block. It can be said that the breaking of the key stratum will lead to the movement and deformation of the overlying stratum in a larger range. With the increase of mining height, the key layer which could have formed the masonry beam structure is further damaged and deformed, forming a broken rock mass with irregular slump. The characteristics of the takeoff zone are that the broken rock mass is irregularly degraded, which indicates that the key layer has entered the falling zone, and the overlying soft rock enters the takeoff zone along with the key layer movement. The movement deformation develops from bottom to top until a key layer is formed again to reach the boundary of the falling zone. Only when the balance of triangular arch is satisfied (1) and the length of the main roof rock block should be more than twice the thickness of the layer (2) can the masonry beam structure be formed, that is to say, the boundary of the caving zone be reached.

\[ h_i > 1.5\{M - \sum_{i=0}^{i-1} h_i(k_i - 1) + \sum h(k_i - 1)\} \]  \hspace{1cm} (1)
\[ l_{10} > 2h_i \]  \hspace{1cm} (2)

Figure 1. Structural Model of Stope

As the working face continues to move forward, the key layer on the boundary of the caving zone will form a dynamic equilibrium structure of masonry beam, and the soft rock on it will coordinate with the deformation of the key layer (key layer 1). The subsidence of each stratum is the same as that of the key layer. If the key layer can also form the dynamic equilibrium structure of masonry beam, the
separation layer with free space will occur at the lower part of key layer 2, when it develops upward to another key layer (key layer 2). Similarly, assuming that the free space under the key stratum n is, the maximum bending subsidence of the stratum at the critical stratum n limit span is expressed as:

$$y_n = \frac{q_n}{E_n I_n} \left[ \frac{5 - 12\alpha}{8} l^4 + \left( \frac{\sqrt{2}}{\omega l} + \frac{1}{2} - \alpha \right) \frac{l^2}{\omega^2} \right]$$  \hspace{1cm} (3)

In the formula, \(q_n\) is the overlying strata load; \(I_n\) is the inertia moment of the hard rock; \(E_n\) is the elastic modulus; \(l\) is 1/2 of the ultimate span of the hard rock: \(\omega = (k / E_n I_n)^{1/4}\), \(\alpha = (\sqrt{2} \omega \times 2l \times 2 + 6ol + 6\sqrt{2}) / [(6ol(2 + \sqrt{2})ol)]\). The Winkler elastic foundation coefficient is \(k\): \(k = \sqrt{(E_0 / d_0)}\). \(E_0\) is the elastic modulus of the foundation and \(d_0\) is thickness of the cushion.

According to the characteristics of the curved subsidence zone, if \(y_n \geq \Delta_n\), it shows that the bending moment of key layer N does not reach the maximum bending moment of key layer N after reaching the ultimate span, and it contacts the overlying soft rock controlled by key layer n-1, that is, key layer N will not break to form masonry beam structure. When the working face continues to advance to full mining, the gangue in the goaf is compacted, and the key layer N will not break to form a masonry beam structure, but will only produce some smaller vertical cracks. \(hF\) is used to express the height of the fracture zone, that is, the distance between the lower layer of the mining layer and the lower layer of the bent subsidence zone.

| Table 1. Relationship between Caving Zone Height and Mining Height |
|---------------------------------|---|---|---|---|---|---|---|
| Rock formation number entering the range of the fall zone | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| Height /m | 2.66 | 7.98 | 7.98 | 32.225 | 32.225 | 39.675 | 39.675 |
| Rock formation number entering the fracture zone | 1 | 3 | 3 | 3 | 3 | 7 | 7 |
| Gob waste rock caving height /m | 2.66 | 7.98 | 7.98 | 32.225 | 32.225 | 39.675 | 39.675 |
| Free space height /\(\Delta\) | 0.34 | 0.02 | 1.02 | 2.275 | 3.275 | 0.825 | 1.825 |
| Falling belt height \(h_{fall}\)/m | 3 | 8 | 9 | 34.5 | 35.5 | 40.5 | 41.5 |
| Direct top thickness \(\Sigma h\)/m | 2 | 6 | 6 | 30.5 | 30.5 | 34.5 | 34.5 |
| Rock stratum within the fissure zone | 1~4 | 1~4 | 1~6 | 1~9 | 1~9 | 1~11 | 1~13 |
| Enter the curved sinker number | 5 | 5 | 7 | 7 | 10 | 12 | 14 |
| Fissure zone height \(h_{fissure}\)/m | 31.5 | 32.5 | 37.5 | 56.5 | 57.5 | 76.5 | 92 |

3. Analysis of Overburden Strata Movement Law at Different Mining Heights

3.1. Modern Establishment and Simulation Schemes
The model takes H Zhuang Mine as the simulation model, and 1/4 model is selected for calculation and analysis. The shape size of the model is 200 m × 200 m × 200 m × 200 m, 208, 000 units. The upper boundary of the model is loaded uniformly according to the thickness of the overlying strata. The vertical displacement of the lower boundary is fixed, and the horizontal displacement of the left and right sides is also fixed. The constitutive relation of the surrounding rock used in the model is the Mohr-Coulomb model. The mechanical parameters of rock are selected according to Table 2. From the upper boundary to the surface of the model, the surrounding rock is added to the upper boundary in the form of uniform load, the magnitude of which is \(P=2500\text{kg·m}^{-3}×10\text{m}^{-2}×500\text{m}=12.5\text{MPa}\).

The simulated goaf is 100m × 100m, and 100m coal pillars are set up according to the boundary conditions. The displacement field, stress field and plastic zone distribution of overlying strata are simulated when mining height is 2m, 3m, 4m, 5m, 6m and 7m.
Table 2. Rock Mechanics Parameters

| Lithology         | Bulk modulus (GPa) | Shear modulus (GPa) | Density (kg/m³) | Cohesion (Mpa) | Internal friction angle (°) | Tensile strength (MPa) |
|-------------------|--------------------|---------------------|-----------------|---------------|-----------------------------|------------------------|
| Fine sandstone    | 2.56               | 2.17                | 2600            | 2.4           | 42                          | 2.5                    |
| Medium sandstone  | 2.73               | 1.38                | 2500            | 2.3           | 40                          | 2.3                    |
| Siltstone         | 2.68               | 1.84                | 2700            | 2.0           | 32                          | 2.0                    |
| Mudstone          | 3.03               | 1.56                | 2200            | 1.2           | 27                          | 1.0                    |
| Oblique porphyry  | 2.42               | 1.32                | 2700            | 1.6           | 35                          | 2.3                    |
| Coal              | 1.19               | 1.17                | 1400            | 0.8           | 23                          | 0.7                    |

Figure 2. Simulation Model and Roof Monitor Lines Layout (unit: m)

3.2. Migration law of overlying strata

3.2.1. Displacement law of overlying strata. Because FLAC3D in the stope mining process can not through the roof collapse and unit fracture form to intuitively judge the face pressure appearance. Therefore, it is an effective method to judge the law of overburden strata in the stope through the dense degree of isoline in the displacement field, the regional distribution and stress concentration in the stress field and the tensile shear failure area in the plastic zone. Due to the limited space, this paper only gives pictures of mining heights of 7m, as shown in Figure 3.

Through the analysis of the displacement field nephogram along the strike and trend of the working face under different mining heights, it can be seen that when the working face is mined to 100m, the working face is close to full mining. At this time, the displacement range of the overlying strata reaches the maximum, the displacement angle of the strata is 83 degrees, and the orientation and strike displacement of the working face are approximately symmetrical distribution. The roof subsidence of overlying strata reaches the maximum at 80m of the goaf, which is equal to the mining height. This means that the roof has completely collapsed and contacted with the floor and compacted, and the roof subsidence will not increase any more, and there will be stress rebound at the side of the goaf. As shown in Table 3, the range of dense isoline generated by roof with different mining heights tends to be non-convergent below the dense isoline, which indicates that the overburden strata are out of balance, the roof is out of continuity, and the strata falling towards the goaf are irregular or layered rock blocks. The displacement tends to converge above the dense isoline, and decreases with the increase of the height of overlying strata. The displacement of the strata above the goaf is obviously larger than that outside the cut-top line (outside the black line in the figure). Because of the support of coal pillars, the displacement outside the cut-top line is only a few millimeters, which can be neglected, while the displacement above the goaf is caused by the caving and fracture of the roof strata.
By deriving the displacement curve of monitoring line 1, it can be seen that the overlying strata behind the stope have already stabilized when the working face is mined to 100m, and the periodic weighting of the stope is about 25m. The vertical displacement 10m away from the floor of the stope is greatly affected by the mining height. The vertical displacement of the roof of overlying strata has obvious stratification phenomenon. With the increase of the distance from the floor height, the vertical displacement tends to be the same under different mining heights.

### Table 3. Displacement Density Contour Range with Various Mining Heights

| Mining Height | 2m  | 3m  | 4m  | 5m  | 6m  | 7m  |
|---------------|-----|-----|-----|-----|-----|-----|
| Dense line height | 15  | 16  | 36  | 38  | 41  | 43  |

### Table 4. Caving Zone and Fractured Zone Height with Various Mining Heights

| Mining Height | 2m  | 3m  | 4m  | 5m  | 6m  | 7m  |
|---------------|-----|-----|-----|-----|-----|-----|
| Caving zone height | 10m | 10m | 33.7m | 34.6m | 38.7m | 40.4m |
| Fissure zone height | 36m | 36.8m | 54.9m | 62.7m | 84.8m | 90m |

3.2.2. Failure law of overlying strata. The plastic zone of the working face is saddle-shaped with high end and low middle. The working face is symmetrical along the direction of strike and inclination. The plastic zone in the middle of the goaf is smaller than that in the upper part of the working face. This is due to the support of the coal wall and the subsidence of the overlying strata on the side of the goaf; which results in the tensile stress above the mining boundary, making the damage scope larger than that in the middle part of the goaf. As the mining height increases, the difference between the plastic area above the mining boundary and the plastic area in the middle decreases. From the bottom to the top of the roof, the order is tensile failure area, shear failure area, shear failure area and undamaged area. Tensile failure zones are mainly distributed in the rock strata above the goaf and are divided into caving zones. Tensile fracture zones are developed in the upper part of the goaf, producing one-way or two-way fissures and dividing into fissure zones. Due to the overall movement of the rock strata in the bent subsidence zone, the subsidence is very small and some fissures produce plastic deformation, local shear failure occurs. The elastic and plastic deformation zones of the model can be divided into bending subsidence zones.
3.2.3. Distribution law of mining stress. By monitoring line 1 and monitoring line 2, we can analyze the pre-support stress and lateral support stress under different mining conditions and come to the conclusion that:

(1) The vertical stresses of the pre-support stress and lateral supporting stresses are disorderly in the side of the goaf. It shows that the rock mass after roof collapse loses continuity and falls irregularly over the floor of the goaf. The subsidence of the overlying strata does not compact the rock mass falling in the goaf. The slight stress rebound in the side of goaf caused by the continuity of flac3D numerical analysis software and the phenomenon is not obvious.

(2) Along the advancing direction of the working face, the roof overburden of the goaf undergoes the state of high stress compression, pressure relief expansion and re-compression, and this process appears periodically with the continuous advance of the work. Therefore, in the roof strata of goaf, roadways are arranged parallel to the working face. In the normal mining stage, roadways are firstly subjected to advance supporting stress. Surrounding rocks produce fissures and enter the goaf. The stress level of surrounding rocks decreases sharply, the mining fissures are released and expanded. As a consequence, the surrounding rocks are fragmented and deformed seriously, resulting in the instability of roadways.

(3) When the vertical stress on the side of solid coal reaches its peak value, it begins to decrease to stability, and after stabilization, the vertical stress value is slightly larger than the original rock stress. With the increase of mining height, the vertical stress after stabilization also increases.

| Table 5. Coefficient of Stress Concentration K |
|-----------------|---------|---------|---------|---------|---------|---------|---------|
| Height          | 2m      | 3m      | 4m      | 5m      | 6m      | 7m      |
| Lead stress     |         |         |         |         |         |         |
| Concentration factor | 1.5248  | 1.6504  | 1.7736  | 1.8984  | 2.0272  | 2.1776  |
| Peak position /m | 3.93    | 5.86    | 7.86    | 9.88    | 11.43   | 13.64   |
| Lateral stress  |         |         |         |         |         |         |
| Concentration factor | 1.5096  | 1.612   | 1.772   | 1.8936  | 2.0192  | 2.1632  |
| Peak position /m | 3.61    | 5.33    | 7.15    | 9.01    | 11.21   | 12.88   |
Monitoring Line 3 Vertical Stress             Monitoring Line 4 Vertical Stress

Figure 7. Advance Support Stress and Lateral Support Stress of Entity Coal

Through monitoring line 3 and 4, the analysis of the vertical stress changes in the pressure boosting zone of the advance support stress and the lateral support stress of solid coal shows that the limit equilibrium zone of the advance support stress and the lateral support stress under different mining heights is very small. The vertical stress of the goaf side is basically the same under different mining heights. When entering the boosting zone, the vertical stress increases with the increase of mining heights. When reaching the peak value, the vertical stress decreases and tends to be stable, and its stability value is larger than the original rock stress.

4. Conclusion
(1) Because of the influence of key strata on different mining heights, the height of fracture zone rises abruptly with the increase of mining heights. Each abrupt change indicates that a key stratum is broken to form a masonry beam structure.

(2) Flac3D simulation is used to analyze the migration law of overlying strata under different mining height conditions. When the mining face reaches 100m, the working face is close to full mining, the movement angle of strata is 83°, and the inclination and strike displacement of the working face are approximately symmetrical distribution. The displacement of the strata above the goaf is obviously larger than that outside the cut-top line. While the displacement above the goaf is caused by the caving and fracture of the roof strata.

(3) The plastic zone of working face is a saddle-shaped distribution with high end and low middle. With the increase of mining height, the difference between the plastic zone above the mining boundary and the plastic zone in the middle decreases. From the bottom to the top of the roof, the order is tensile failure area, shear failure area, shear failure area and undamaged area. Tensile failure zones are mainly distributed in the rock strata above the goaf and are divided into caving zones. Tensile fracture zones are developed in the upper part of the goaf, producing one-way or two-way fissures and dividing into fissure zones. Due to the overall movement of the rock strata in the bent subsidence zone, the subsidence is very small and some fissures produce plastic deformation, which bring about local shear failure. The elastic and plastic deformation zones of the model can be divided into bending subsidence zones.

(4) The vertical stress of the leading support stress and the lateral support stress on the side of the goaf is disorderly, which indicates that the rock mass after roof collapse loses continuity and falls irregularly above the floor of the goaf, and the subsidence of the overlying strata does not compact the rock mass falling in the goaf. With the increase of mining height, the advance stress concentration factor and the lateral stress concentration factor increase linearly, and the lateral stress concentration factor is slightly lower than the advance stress concentration factor. The peak position increases with the increase of mining height.

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