Evolution Characteristics and Instability Analysis of Stratified Roof Structure in Roadway with Different Stress Levels

Jichun Kang,* Jiayi Guo, Yajun Xin, and Sijiang Wei

ABSTRACT: With the extension of mines to deep mining, horizontal stress has become an important factor in the stability of the roadway surrounding rock, and the influence of horizontal stress on the structure of a layered roof is more complex. The simulation test of a layered roof of a roadway under different lateral pressure coefficients was carried out by using a self-designed test device and discrete element simulation software. The crack coalescence behavior of a layered roof in a roadway was analyzed, and the critical stress of rock beam failure in each layer was determined. The results show that the larger the stress levels, the larger the number and height of cracks in the layered roof were, and the relationship between them can be characterized by a quadratic polynomial. With the increase of stress levels, the layered roof was damaged gradually from the bottom to the top along the bedding plane. The maximum height of the roof caving was 9, 23, 31, and 39 mm, respectively. The width of the upper roof caving was 72, 35, 31, and 27 mm in turn. The left angle of the caving range had little change (about 60°). With the increase of stress level, the maximum caving height of the layered roof tended to increase, while the width of the top surface tended to decrease. The relationship between the stress level and the height and width can be represented by a quadratic polynomial and exponential function. According to the stability theory of the compression bar, the critical stress of failure and the decrease of the span of the rock beam in each layer were determined respectively, and the reasons for the instability of the layered roof caving are explained.

INTRODUCTION

The coal measure strata have obvious structural characteristics of a layered rock mass.1 In order to maintain the integrity of the roadway roof, the roadway is usually excavated along the rock roof. When the strength of the roadway roof is low (such as the common mudstone roof), the strength of its joint and fissure development is very low, and the broken range of the roof in this kind of roadway often exceeds the length of the bolt. According to the suspension theory,2 the anchor cable plays a vital role in this case, and it must be anchored in a stable area. At this point, the potential caving range of the layered roof is particularly important. Proctor’s theory3 is often used to calculate the height of the roof caving arch, and it analyzes the roadway surrounding rock as a homogeneous body without considering the stress state of the surrounding rock. A large number of studies show that the main factor of the roadway roof and floor failure is horizontal stress rather than vertical stress.4−8 Therefore, studying the caving of the layered roof under the condition of horizontal stress will be conducive to the selection of basic support parameters of a layered roof in a deep mining roadway.

At present, many scholars have studied the relationship between horizontal stress and roof stability and horizontal stress and the failure of layered roof. Through numerical simulation, Lin showed that the layered rock roof is mainly separated and bent under the action of horizontal compressive stress, rather than directly damaged in the form of a bearing beam under the action of vertical pressure.9 Yang et al. regarded the layered strata of the coal roadway roof as thin plates and derived the calculation formula of buckling critical stress.10 Fan et al. analyzed the failure types and characteristics of rock strata with the weak structure of the roof and floor.11 Jia et al. analyzed the failure law of the layered roof under different lateral pressures and different thickness span ratios by using RFPA.12 Jia used RFPA to numerically simulate the deterioration process of layered roofs with different combinations.13 Zhang et al. revealed the mechanical mechanism of roof instability from the analysis of asymmetric action of

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inclined strata, horizontal tectonic stress, weak instability of the coal wall, and plastic flow induced by floor heave.\textsuperscript{14} Gu et al. presented the calculation method of the roof caving arch height of the layered rock roadway.\textsuperscript{15} Luo et al. discussed the form of equilibrium arch and its rise height formed by the caving of the layered roof rock mass.\textsuperscript{16} Based on the elastic thin plate theory, Yu et al. conducted mechanical analysis on the layered roof with small single layer thickness of the roadway, established thin plate mechanical models of layered roof strata under different boundary conditions, and obtained stress distribution characteristics and fracture mechanism of roof strata by the numerical simulation analysis.\textsuperscript{17} Based on the Kirchhoff analogy theory of an elastic sheet, Ding studied the mechanics model and put forward the roadway composite roof strata instability discriminant method.\textsuperscript{18} Zhou et al. proposed an elastoplastic analysis method for the three-way bearing beam structure of the roadway layered roof.\textsuperscript{19} Feng et al., for the same roadway in different areas of the composite roof caving problem, established the roadway composite roof strata beam structure mechanics model and put forward the roadway composite roof strata instability discriminant method.\textsuperscript{20} Based on the beam theory and block theory, Chen et al. constructed the beam-block mechanical model of roof rock to reveal the variation law of the direct roof failure mode in the weak layer.\textsuperscript{21}

It can be seen that the research methods of layered roof stability under horizontal stress are mostly theoretical calculation and numerical simulation. In this paper, the self-designed test frame is used to test the failure process of the horizontal equal thickness layered roof under different horizontal stresses, and strives to reproduce the failure process and caving form of the roadway roof under such conditions. According to the experimental phenomenon and the stress state of the roof, the layered roof compression model is established, and the caving process of the layered roof is explained by theory. The research results can provide a basis for the selection of support parameters of the deep layered roof roadway.

![DEFORMATION AND FAILURE CHARACTERISTICS OF SURROUNDING ROCK IN LAYERED ROOF ROADWAY](http://pubs.acs.org/journal/acsodf)

The main influencing factors of deformation and failure characteristics of a layered roadway roof are the stress state of surrounding rock and the mechanical structure characteristics of the surrounding rock and roadway section. Due to the existence of a bedding plane, the deformation and failure characteristics of a layered roof are quite different from those of a continuous rock mass. In general, under the influence of horizontal force, layered roof caving in the excavation process has the following characteristics:\textsuperscript{10,13}

1. The roof caving develops gradually upward from the bottom layer of the roof. Under the action of horizontal stress, the failure modes of each layered roof rock beam are compressive bending failure and shear failure.

2. The ratio of layer thickness to span of a mining roadway in China is less than 1/7, which can be regarded as thin-layer rock stratum. The main reason for bottom rock beam caving is flexural instability.

3. With the upward development, the span of the upper rock beam gradually decreases, resulting in an increase in the ratio of layer thickness to span. The main reason for the rock beam caving changes to shear failure.

### SIMILAR SIMULATION TEST DESIGN

The engineering background of the test is the track roadway of a mine. The roadway is excavated along the roof of the coal seam. The direct roof of the roadway is composed of thick layered mudstone. The roof and floor are shown in Table 1.

| Layer | Main roof | Immediate roof | Immediate bottom | Old bottom |
|-------|-----------|----------------|------------------|------------|
| Rock name | Siltstone | Mudstone | Sandy mudstone | Fine sandstone |
| Rock thickness (m) | 4.46 | 16.8 | 1.78 | 11.46 |

The strength of the mudstone roof is low. After the influence of water and weathering conditions, the overall mechanical properties will decrease sharply. The geological structures such as faults and anticlines encountered in the process of roadway excavation will cause different horizontal stress states, resulting in different failure modes and ranges of roof, which seriously affects the normal use of the mining roadway. In order to further understand the roof caving characteristics of a layered roof mining roadway under different horizontal stress conditions in deep, and to select reasonable support parameters, this experiment was designed.

**Test Model and Parameter Determination.** The self-made test device is used for the test, as shown in Figure 1. The maximum simulation size is 800 mm × 800 mm × 200 mm. The loading system was composed of the top and both sides of the cylinder. The cylinder stroke is 100 mm, the maximum pressure is 7 MPa, the height is 37.1 mm, the cylinder diameter is 125 mm, and the rod diameter is 50 mm.

According to the research needs, nine L-shaped extraction plates with different sizes are placed in the middle of the floor. During the test, the L-shaped extraction plates are extracted according to the needs of the simulation size, and the exposed similar simulation materials are used to simulate the roadway roof. In the similar simulation test, the selected similar simulation materials are first loaded into the box through the feed port. After the material strength meets the requirements, the upper hydraulic cylinder is operated to apply vertical load, and then the left hydraulic cylinder and the right hydraulic cylinder are operated to apply horizontal load. The horizontal stress is loaded step by step according to the designed pressure. At the same time, the height and shape of the caving range of the roadway roof are observed through the transparent Plexiglas plate, and one or more extraction plates are extracted according to the roadway width in the coal mine. Finally, the variation law of caving arch under the condition of horizontal stress is analyzed through the data.

Considering the model frame size and other factors, the following similarity constants are determined: model geometric constant 1/50, bulk density similarity constant 0.6, and strength similarity constant 0.012.

The uniaxial compressive strength of the on-site sampling specimen is less than 7 MPa. The overall characteristics of the rock are as follows: low strength, loose structure, developed joints, poor resistance to water immersion and weathering, and easy to soften. Therefore, the proportioning scheme as shown in Table 2 is determined.

**Experimental Design and Process.** If the buried depth of roadway is about 400 m, the vertical stress is 10 MPa, and
the lateral pressure coefficient \( \lambda \) is 0, 0.5, 1.0, 1.5, 2.0, and 2.5 in turn.

The specific test process is as follows:

1. According to the amount of layered materials calculated in Table 2, the required river sand, calcium carbonate, and gypsum are weighed with a scale or balance, and then mixed evenly. Retarder (borax) and water are added to the mixture to make it mix evenly.

2. The mixture is poured into the model frame, leveled with a scraping batch, tamped and compacted with a rubber hammer, paved as smoothly as possible, and a layer of mica evenly sprinkled every 10 mm to simulate the weak surfaces such as layering and joint fissures of rock stratum, make its bedding clear, and lay it to the design height.

3. After the model has been laid and dried for 1 week, both sides of the organic plastic plate are removed, and the surface is allowed to continue drying for 3 days.

4. An 80-mm-long L-shaped extraction plate is taken to simulate excavation of roadway.

5. According to the loading scheme of pressure, the caving shape is drawn. The test model and measuring point arrangement are shown in Figure 2.

**ANALYSIS OF SIMILAR SIMULATION TEST RESULTS**

**Development and Evolution Law of Roof Fissures.** Since the observation cracks on the back of the test frame are not affected by the arrangement of measuring points, the development process of cracks on the back roof is studied, as shown in Figure 3. It can be seen that with the increase of lateral pressure coefficient, the interlayer cracks are from less to more, the height of cracks is rising, and the range is increasing. When \( \lambda = 0.5 \), cracks begin to appear on the upper right of the roof, the number of cracks is 1, and the height of cracks is 9 mm. When \( \lambda = 1.0 \), the interlayer cracks continue to expand, and the length is equivalent to the width of the roof, with the number of cracks 2 and the height of cracks 12 mm. When \( \lambda = 1.5 \), the strata have broken and begun to fall. The number of fractures is 4 and the height of fractures is 15 mm. When \( \lambda = 2.0 \), the interlayer cracks expand upward, and the height and

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**Table 2. Top and Floor Conditions**

| Rock stratum name | Compressive strength/ kPa | Prototype thickness/m | Layer thick/cm | Sand/kg | Calcium carbonate/kg | Gypsum/kg | Water/kg | Borax/kg |
|-------------------|---------------------------|-----------------------|----------------|---------|----------------------|-----------|----------|----------|
| Mudstone          | 68.5                      | 17                    | 34             | 2.1     | 0.21                 | 0.09      | 0.3      | 0.004    |

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**Figure 1.** Testing apparatus.

**Figure 2.** Testing model and measurement points.
The number of cracks increase sharply by 7 mm and 29 mm, respectively.

The relationship between lateral pressure coefficient and fracture number is shown in Figure 4. Fitting the number of fractures and the lateral pressure coefficient is

\[ N = 2\lambda^2 - \lambda + 1 \] (1)

where \( N \) is the number of fractures and \( \lambda \) is the lateral pressure coefficient. The correlation coefficient is \( R^2 = 1 \). It shows that an exponential function can better characterize the relationship between the number of fractures and the lateral pressure coefficient.

It can be seen that under the condition of increasing lateral pressure coefficient, the number of fractures shows an increasing trend, and the increase is larger and larger. The influence of the lateral pressure coefficient on the number of fractures is obvious.

The relationship between lateral pressure coefficient and fracture height is shown in Figure 4. Fitting the fracture height and the lateral pressure coefficient is

\[ c = 0.8155 \exp\left(\frac{-\lambda}{0.6149}\right) + 7.106 \] (2)

where \( c \) is the fracture height and \( \lambda \) is the lateral pressure coefficient. The correlation coefficient is \( R^2 = 0.989 \). It shows that the exponential relation can better characterize the relationship between fracture height and lateral pressure coefficient.

It can be seen that under the condition of increasing lateral pressure coefficient, the fracture height shows an increasing trend, which first increases slowly, and then increases more and more. The influence of lateral pressure coefficient on fracture height is obvious.

**Variation Characteristics of Roof Caving Parameters.** In the process of loading horizontal stress step by step, the roof gradually falls from bottom to top along the layer. The process of fracture and falling is shown in Figure 5, and the sketch of roof falling process is shown in Figure 6. When only vertical stress is applied, the roadway roof has small cracks and no obvious deformation. When \( \lambda = 0.5 \), the roof has obvious vertical displacement and two long arc cracks appear. When \( \lambda = 1.0 \), the roof caves along the horizontal bedding, but the maximum caving width is less than the roof width. When \( \lambda = 1.5–2.5 \), the roof continues to fall gradually layer by layer, and the maximum caving width is equal to the roof width. With the increase of horizontal force, the layered roof falls gradually.

![Figure 3. Process of crack development.](image)

![Figure 4. Relationship between lateral pressure coefficient and fracture number, fracture height, and caving height.](image)
along the bedding plane from bottom to top, and the caving span decreases continuously. The caving shape is generally similar to the trapezoidal.

Figure 4 reflects the relationship between the lateral pressure coefficient and caving height. It can be seen that with the increase of lateral pressure coefficient, the maximum height of falling is 9, 23, 31, and 39 mm, respectively, with an increase of 156%, 35%, and 26%. With the increase of lateral pressure, the increase of caving height is significantly slowed down.

Fitting the relationship between caving height and lateral pressure coefficient is

\[ d = -64\lambda^2 + 40.6\lambda - 25.3 \]  

where \( d \) is caving height (mm) and \( \lambda \) is the lateral pressure coefficient. The correlation coefficient is \( R^2 = 0.989 \), It shows that a quadratic polynomial can better characterize the relationship between caving height and lateral pressure coefficient.

Figure 7 shows the relationship between the lateral pressure coefficient and the caving width. The top surface width of the caving is 72, 35, 31, and 27 mm in turn. It can be seen that with the increase of horizontal pressure, the caving height is increasing, and the top surface width is indeed decreasing. The decrease is sharply reduced from 51% to 13%, and the trend is obviously slowed down. The relationship between the width of the upper surface of roof caving and the lateral pressure coefficient is fitted by

\[ b = 1542.72 \exp\left(-\lambda/0.28096\right) + 28.05 \]  

where \( b \) is the width of the upper surface and \( \lambda \) is the lateral pressure coefficient. The correlation coefficient is \( R^2 = 0.9891 \), which shows that the exponential relationship can better characterize the relationship between the width of the top surface and the lateral pressure coefficient.

Figure 8 shows the relationship between the lateral pressure coefficient and the angle on the left side of the caving range, which are 62°, 64°, and 57°, respectively. It can be seen that there is little change, all around 60°.
MECHANICAL MODEL OF LAYERED ROOF STRUCTURE

Influence of Lateral Pressure Coefficient on Layered Roof. The existence of a large number of horizontal or inclined planes in a layered rock mass not only makes the anisotropy of rock mass very obvious but also cause discontinuity of the rock mass, so that the caving form of the surrounding rock is different from the parabolic form in the homogeneous rock mass. According to the test phenomenon, the schematic diagram of layered roof caving under the condition of progressive loading of horizontal stress is shown in Figure 9.

The underground engineering practice shows that under the pressure parallel to the bedding direction, the flexural instability failure of the roof rock beam is gradually developed from bottom to top. The same is true in the test process. Under the action of increasing horizontal stress, the rock beam at the lowest layer of the layered roof deflects and separates the layer, as shown in Figure 9a, and its span is the width of the roadway. When the tensile stress in the middle of the rock beam exceeds the tensile strength of the rock, and the shear stress at both ends exceeds the shear strength of the rock, the bottom rock beam will be damaged in the center and two ends, and then fall, leaving shear fracture surfaces at both ends, such as Figure 9b and c. With the continuous increase of horizontal stress, the layered roof gradually falls upward layer by layer. Because the shear fracture surface is narrow at the top and wide at the bottom, it is equivalent to reducing the span when the layered rock mass in the upper part falls, so the caving shape as shown in Figure 9d is formed.

Construction of a Layered Roof Structure Model. According to the caving phenomenon and stress state of the layered roof, the following assumptions are first made:

1. After the roadway excavation, the vertical stress in the roof decreases to zero, the horizontal force of the roof strata is only affected by the horizontal force, and the self-weight is ignored.
2. The layered roof is destroyed layer by layer from bottom to top; that is, the bottom of the roof is destroyed and then separated from the upper layer, the upper narrow and lower wide fracture surfaces are left at both ends, and then the upper layer is destroyed with the increase of horizontal stress.
3. The span of a mining roadway in China is mostly 3 6m, and the ratio of layer thickness to span is less than 1/7, which can be regarded as a thin layer rock stratum. The main reason for the bottom rock beam caving is flexural instability.

Based on the above assumptions, the layered roof compression model is established as shown in Figure 10.

According to the stability theory of the compression bar in material mechanics, it is considered that when the horizontal force $P_x$ is greater than or equal to the critical load $P_{cl}$, the bottom rock stratum $h_1$ is flexural instability. Then, the critical load of the bottom rock beam of the roof is

$$P_{cl} = \frac{\pi^2 EI}{(\mu l_1)^2}$$

where the $\mu$ is length coefficient; for rock beams fixed at both ends, $\mu$ is 1; $l_1 = h_1$ is length of rock stratum (m); $E$ is elastic modulus of rock roof (MPa); $I$ is inertia distance of section to neutral axis, $I = \frac{bh^3}{12}$; $b$ is rock beam width, taking unit length; and $h_1$ is thickness of stratum (m).

The critical instability stress of the bottom rock beam is

$$\sigma_{cl} = \frac{P_{cl}}{h_1} = \frac{\pi^2 E I_2}{12 h_1^2}$$

where $i_1$ is thickness–span ratio of the bottom layer, $i_1 = \frac{h_1}{l_1}$.

The critical load and stress of the upper rock stratum are similar.

Determination of Span Reduction Value. As for the phenomenon in which the span decreases when the roof is damaged layer by layer, some researchers believe that a pair of cantilever beams are left behind after the collapse of the...
horizontal layered rock mass, which may become the base of the horizontal layered rock mass above it, and the span of the horizontal layered rock mass beam above the tunnel top will gradually decrease. Some researchers also believe that after the first layer of the rock beam flexure failure, due to the release of horizontal stress, the rock beam rebounds and displaces along the bedding direction, resulting in the step dislocation of upper and lower rock layers, which reduces the actual length of the second layer of rock beam, but no specific algorithm for reducing the value is given. According to Platts’ theory, the paper assumes that the caving shape is a parabola and obtains the span reduction value through calculation. The paper states that the span reduction value should be the thickness of the lower rock layer, and the thickness of the lower rock layer is the reduction value of the upper rock layer in this paper. Then, the critical instability stress of the rock beam in layer \( n \) can be obtained as

\[
\sigma_{\text{cr}} = \frac{\pi^2 E}{12} \frac{h_n}{i_n}
\]

where \( i_n \) is the thick span ratio of layer \( n \).

According to the compression bar stability theory and Mohr’s strength theory, the failure critical stress and span reduction value of rock beam in each layer are determined. If we assume \( h = 0.1 \text{ m}, \phi = 25^\circ, l_1 = 5 \text{ m}, \text{ and } E = 15 \text{ GPa} \), and substitute these into formulas 6 and 7, the horizontal stress of flexural instability in each layer can be obtained, as shown in Figure 11.

![Figure 11. Curve of critical stress.](image)

It can be seen from the curve in Figure 11 that the continuous upward failure of the layered roof requires the continuous increase of horizontal stress, and the more upward the development is, the greater the increase will be. However, the similar simulation caving develops upward, and the increase will be significantly reduced as shown in Figure 4. This is because the middle and two ends of the roof rock beam will be damaged gradually in the process of increasing horizontal stress, which means that the elastic modulus is decreasing continuously. As a result, the increase of horizontal stress that needs to be continuously increased in the upward failure of layered roof will decrease, and with the increase of stress exceeding the compressive strength of rock, the shear failure of rock beam will occur directly.

## CONCLUSIONS

The greater the lateral pressure coefficient, the greater the number and height of cracks in layered roof, which can be characterized by exponential function and quadratic polynomial, respectively.

With the increase of lateral pressure coefficient, the layered roof gradually falls layer by layer along the bedding surface from bottom to top. The maximum height of falling is 9, 23, 31, and 39 mm, respectively. The width of the upper top surface of roof falling is 72, 35, 31, and 27 mm in turn, while the angle on the left side of the falling range changes little (about 60°).

With the increase of the lateral pressure coefficient, the maximum caving height of the layered roof shows an increasing trend, and the width of top surface of caving shows a decreasing trend. The lateral pressure coefficient, caving height, and width can be characterized by quadratic polynomial and exponential function, respectively. The failure critical stress equation of each rock beam is closely related to the lateral pressure coefficient.

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### Notes

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