Structural Feature and Evolution Mechanism of Arch Structure for Thick Unconsolidated Layer

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Structural feature and evolution mechanism of arch structure for thick unconsolidated layer

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Abstract: Traditionally, the study on the bearing structure of overlying strata mainly focuses on bedrock with the effect of the overlying unconsolidated layer. It simply considered as uniformly loading on the top interface of the bedrock, and ignores the bearing structure for unconsolidated layer. Combined with the geological conditions of shallow burial thick unconsolidated layer in Shendong mining area, the mechanical model of the arch structure for the unconsolidated layers was established. The relationship between the arch height and span was analyzed with theoretical formula and the dynamic evolution mechanism of arch structure was studied with numerical simulation. Besides, formula of arch structure ultimate height was derived. The influence mechanism of arch structure on ground fissures was revealed and criterion was obtained, which was verified by field monitoring data. Furthermore, a classification method of arch structure in thick unconsolidated layers was proposed.

Key words: thick unconsolidated layer; arch structure; evolution mechanism; ultimate height; ground fissures

Many hypotheses and structural models have been developed in the research process of mining pressure and rock strata control. Such as "voussoir beam", "transferring rock beam structure", "cantilever beam" and so on (Qian, 2010; Qian, 2003; Song, 1988). These theories simplify the unconsolidated layer to uniformly loading on the main roof of the bedrock (key layer), but ignore the bearing structure of thick alluvium (Wang et al., 2019). By the field measurement, the collapse weight of thick alluvium on the surface (mainly the sandy soil layer) does not act on the key blocks of the main roof all at once, there is the "unconsolidated layer arch" bearing structure when shallow burial coal seam is mined (Huang, 2018).

As for the research on the arch structure in the thick alluvium, Huang Qingxiang found that thick alluvium of shallow burial coal seam has "arch effect " through physical similarity simulation experiment, and the height of "unloading arch" during the initial weighting is determined by using the Pratt's arch mechanics model (Huang, 2004); Du Feng established the stress arch mechanics model of thick alluvium and thin bedrock, then he obtained the relationship between arch span and arch height (Du, 2012); Wang Feng established the mechanical model of the bearing structure for the unconsolidated layer arch and revealed its shape equation, vector - span ratio equation and thickness equation, the theoretical expression of the critical thickness of unconsolidated layer is obtained when the arch of unconsolidated layer is formed (Wang, 2016). Zuo Jianping founded the "analogous hyperbola" model of thick alluvium, then obtained the calculation formula of surface subsidence range (Zuo, 2017; Zuo, 2018). Huang Qingxiang established the "arch beam" structure model of thick sandy soil layer, and provided the cracked criteria of thick sandy soil layer (Huang, 2009). The existed research results have promoted the development of the unconsolidated layer arch model, but further study is needed. On the basis of predecessors' research, the author simplifies thick alluvium arch to three hinged arch mechanical model under the action of filling soil pressure. The shape equation, thickness equation and the relationship between arch height and span are obtained. In this paper,
the dynamic evolution mechanism of arch bearing structure in the process of coal mining is studied, and the mining-induced unconsolidated layer structure is classified according to the unconsolidated layer thickness, the research results are verified by the measured data, which has a certain guiding significance for the research on the development law of mining overburden and the development mechanism of ground fissures under the condition of thick alluvium.

1 The arch structure for thick unconsolidated layer for shallow burial coal seam

After shallow burial coal seam working face was mined, mining-induced overburden structure is broken and then gradually develops upward to the unconsolidated layer. The internal medium of unconsolidated layer deformation occurs, uneven displacement occurs between particles, the transfer effect of the force between the lower and the overlying unconsolidated layer disappeared and separated, and the main axial compressive stress was formed in the particles of the overlying unconsolidated layer. The bearing structure which can not only transfer the load between the particles in different areas of the unconsolidated layer, but also play the bearing role on the mining-induced overburden and protect the working face, is described as unconsolidated layer arch structure. The arch structure of unconsolidated layer is mainly composed of the arch body and the support at the arch base. The arch body of the unconsolidated layer arch structure mainly bears axial compressive stress, while the supporting force at the arch base can bears vertical compressive stress, horizontal thrust and bending moment simultaneously. The bearing structure of the overlying strata is shown in Fig.1. The bearing structure in the bedrock is the structure of key layer, the bearing structure in the unconsolidated layer is the unconsolidated layer arch structure.

2 The mechanics model of the unconsolidated layer arch structure

The bearing structure of unconsolidated layer arch is simplified appropriately and the mechanical model is established (Liu,2011);

(1) The thickness of the unconsolidated layer arch is consistent from the arch top to the arch base, the reasonable arch axis of the unconsolidated layer arch is studied by analyzing the middle surface curve;

(2) The unconsolidated layer arch structure is simplified as three hinged arch, in other words, the reasonable arch axis of the three hinged arch is taken as the reasonable arch axis of the unconsolidated layer arch structure;

(3) The unconsolidated layer arch is filled with the soil, it is under the weight loading of filled soil;

(4) Given the shallow burial coal seam, assuming that the horizontal stress is zero.
The rectangular coordinate system is established with the top point of the arch as the origin, as shown in Fig.2. The distance from the arch top to the surface is the overburden thickness \( H \), arch height is denoted by \( H \), arch span is denoted by \( L \), and the unconsolidated layer arch is subject to soil filling load,
\[
q(x) = \gamma(H + y)
\]
Where \( \gamma \) is the bulk density of the unconsolidated layer [N/m³].

2.1 Arch structure characteristic equation of unconsolidated layer

The equation of reasonable arch axis for three hinged arch is generally expressed as:
\[
y = \frac{M^0(x)}{F_H}
\]
(1)

where \( M^0(x) \) is the bending moment of simply supported beam under filling load [KN·m], \( F_H \) is the reaction force of the horizontal support [KN].

Take the second derivative of both sides of equation (1):
\[
y'' = \frac{1}{F_H} \frac{d^2 M^0}{dx^2}
\]
(2)

The equilibrium differential equation of straight bar segment is approximately applied
\[
\frac{d^2 M^0}{dx^2} = -q(x)
\]
Equation (2) is:
\[
y'' = \frac{d^2 y}{dx^2} = -\frac{q(x)}{F_H}
\]
(3)

In Equation (3), it is specified that the Y-axis upward is positive:
\[
\frac{d^2 y}{dx^2} = \frac{q(x)}{F_H}
\]
(4)

Substituting \( q(x) = \gamma(H + y) \) into equation (4):
\[
\frac{d^2 y}{dx^2} - \frac{\gamma}{F_H} y = \frac{\gamma H}{F_H}
\]
(5)

The general solution of the differential equation can be expressed by hyperbolic function;
\[
y = A \text{ch} \sqrt{\frac{\gamma}{F_H} x} + B \text{sh} \sqrt{\frac{\gamma}{F_H} x} - H
\]
(6)

According to boundary conditions:
When \( x = 0, y = 0, A = H \)
When \( x = 0, y' = 0, B = 0 \)
Therefore, the reasonable arch axis equation can be written as
\[
y = H \left[ \text{ch} \sqrt{\frac{\gamma}{F_H} x - 1} \right]
\]
(7)
That is, under the action of filled weight loading, the reasonable axis of the three hinged arch is a catenary.

2.2 Mechanical model of unconsolidated layer arch structure

Fig. 3 Mechanical analysis of arch structure

Fig. 3 shows the stress analysis of the right arch for the unconsolidated layer arch structure. The overlying load of soil for the unconsolidated layer arch: \( q(x) = \gamma H \tanh \left( \frac{y}{F_H} x \right) \), when \( m = \frac{\gamma}{F_H} \), then the reaction of the horizontal support is:

\[
F_H = \frac{\gamma}{m^2} \quad (8)
\]

According to equilibrium equation in the vertical direction \( \sum F_y = 0 \), when \( \int_0^l q(x) \, dx - F_v = 0 \),

\[
F_v = \frac{\gamma H}{m} \text{sh} \left( \frac{ml}{2} \right) \quad (9)
\]

According to the moment balance equation of hinge Point C \( \sum M_c = 0 \),

\[
F_H \times h = F_v \times \frac{l}{2} - \int_0^l q(x) \, dx \quad (10)
\]

Substituting equation (8) and equation (9) into equation (10) and simplified:

\[
h = H \text{ch} \left( \frac{ml}{2} \right) - H \quad (11)
\]

According to the Taylor expansion of the hyperbolic function

\[
\text{sh} x = x + \frac{x^3}{6}, \quad \text{ch} x = 1 + \frac{x^2}{2} + \frac{x^4}{24}
\]

Equation (11) can be simplified as

\[
m^4 l^4 + 2Hm^2 l^2 - 16h = 0
\]

Obtained:

\[
m = \frac{2}{l} \sqrt[4]{\frac{24H}{H} + 36} - 6 \quad (12)
\]

Selecting appropriate arch height H, arch span L and overburden thickness H and substituting them into
Formula (12) to calculate the value of \( m \), Substituting it to Formula (11) to calculate the \( \epsilon^* \) of the relative error limit \( \epsilon^* \), The expression is

\[
\epsilon^* = \frac{h - h^*}{h} = \frac{h - Hch\left(\frac{ml}{2}\right) + H}{h}
\]

The change of relative error \( \epsilon^* \) with parameters \( H \) and \( H \) is shown in Fig.4 and Fig.5.

(1) The relative error \( \epsilon^* \) increases with the increase of arch height \( H \) and decreases with the increase of overburden thickness \( H \);

(2) When \( h \) and \( H \) vary within a certain range, The relative error \( \epsilon^* \ll 1 \), equation (12) is right.

By substituting equation (12) into equation (8) and equation (9), it can be simplified as:

\[
F_H = \frac{\gamma l^2}{4\sqrt{\frac{24h}{H} + 36 - 24}}
\]  
(13)

\[
F_V = \frac{\gamma H l}{12\sqrt{\frac{24h}{H} + 36}}
\]  
(14)

2.3 Analysis of arch structure stability of unconsolidated layer

According to the research results of K. Terzaghi (Terzaghi, 1960) for the unconsolidated layer arch, the condition of the arch structure stability for the unconsolidated layer is:

\[
F_H \leq F_V \tan \varphi + \frac{1}{2} Cl
\]  
(15)

Where \( \varphi \) is the internal friction angle of the unconsolidated layer,\(^\circ\); \( C \) is the cohesion of the unconsolidated layer,\( \text{[Pa]} \).
Substituting equation (13) and (14) into equation (15), the arch height \( h \) of the unconsolidated layer under the ultimate state can be obtained as:

\[
    h = \frac{H}{24} \left[ \frac{3l}{H \tan \varphi} + \left(3 + \frac{3C}{\gamma H \tan \varphi}\right)^2 - \frac{3C}{\gamma H \tan \varphi} + 3 \right]^2 - 36H
\]  

Defined the thickness of the unconsolidated layer as \( \sum H = H + h \), the span \( l \) of the unconsolidated layer under the ultimate state is:

\[
    l = \left( \frac{\tan \varphi}{3} \sqrt{36 \sum H - 12h} \left( \sum H - h \right) + \frac{2C}{\gamma} \right) \times \left( \sqrt{36 \sum H - 12h} - 6 \right)
\]

Fig. 6 Variation of \( h \) with \( l \) under different unconsolidated layer thicknesses

It can be seen from Fig. 6, with the increase of span \( L \), the arch height \( H \) of the unconsolidated layer under the ultimate state presents a nonlinear increase and the growth rate gradually decreases. The greater the thickness of the unconsolidated layer \( \Sigma H \), the greater the arch limit arch height \( H \) and the ultimate span \( L \) of the unconsolidated layer.

2.4 The formation condition and limit height

(1) The formation condition of unconsolidated layer arch structure

According to the Mohr-Coulomb strength criterion, the maximum and minimum principal stress of the arch foundation should be satisfied in order to form the arch with stable bearing capacity:

\[
    \sigma_1 = \sigma_3 \tan^2 \left( \frac{\pi}{4} + \frac{\varphi}{2} \right) + 2C \tan \left( \frac{\pi}{4} + \frac{\varphi}{2} \right)
\]

Where \( \sigma_1 \) is the maximum principal stress, \( \sigma_3 \) is the minimum principal stress.

Through theoretical analysis, the maximum and minimum ultimate principal stress at the arch foundation of the unconsolidated layer is obtained:

\[
    \begin{align*}
    \sigma_{1f} &= \frac{\gamma H l}{2d \cos \varphi} \\
    \sigma_{3f} &= \gamma (h + H)
    \end{align*}
\]

Where \( \sigma_{1f} \) is the maximum ultimate principal stress at the arch foundation of the unconsolidated layer, \( \sigma_{3f} \) is the minimum ultimate principal stress at the arch foundation of the unconsolidated layer, \( d \) is the thickness of the unconsolidated layer.
Substituting equation (19) into equation (18), the arch thickness of the unconsolidated layer is obtained

$$\delta = \frac{\gamma H I}{2 \cos \phi \tan \left(\frac{\pi}{4} + \frac{\phi}{2}\right) \gamma (h + H) \tan \left(\frac{\pi}{4} + \frac{\phi}{2}\right) + 2C}$$

As shown in Fig.1, when the sum of unconsolidated layer thickness $\Sigma H$ is greater than the sum of unconsolidated layer arch height $H$ and one half of arch thickness $\delta/2$, the unconsolidated layer is arched. Otherwise, no "arch" structure will be formed in the unconsolidated layer:

$$\sum H \geq h + \frac{\delta}{2} \quad (20)$$

(2) Limit height of unconsolidated arch structure

1. Minimum arch height of unconsolidated layer arch

The span when the working face appears first weighting is defined as $l_{初}$. Uneven subsidence of unconsolidated layer is happened. The bearing structure of unconsolidated layer arch is formed for the first time. The minimum arch height of the unconsolidated layer arch is

$$h_{min} = \frac{H_0}{24} \left[ \frac{3l_{初}}{H_1 \tan \phi} + (3 + \frac{3C}{\gamma H_1 \tan \phi})^2 - \frac{3C}{\gamma H_1 \tan \phi} + 3 \right] - 36H_0 \quad (21)$$

$$l_{初} = L_{初} - 2 \sum M \cdot \cot \alpha \quad (22)$$

Where $l_{初}$ is the arch span of unconsolidated layer when the working face appears first weighting, [m]; $\Sigma H$ is the thickness of bedrock layer, [m]; $\alpha$ is the fracture Angle of overburden rock layer, [$^\circ$]; $L_{初}$ is the initial weighting of the working face, [m]; $H_0$ is the thickness of the overlying layer for the unconsolidated arch at the first weighting, [m].

2. Ultimate arch height of unconsolidated layer

With the advance of the working surface and the periodic fracture of the key strata, the arch bearing structure of the unconsolidated layer collapsed and developed upward. When the advanced distance is greater than the working face length, according to the plane strain theory (Xu, 2016), the unconsolidated arch structure will no longer develop upward. As shown in Fig.8, the arch inclination span is (Xu, 2018; Zuo,2019).

$$l_{倾} = D - 2 \sum M \cdot \cot \alpha \quad (23)$$

Where $D$ is the inclination length of working face, [m].

Fig.7 Ultimate span of the arch structure $l_{倾}$

The limit height $h$ of the arch structure for the unconsolidated layer is:

$$h_{倾} = \frac{H_1}{24} \left[ \frac{3l_{倾}}{H_1 \tan \phi} + (3 + \frac{3C}{\gamma H_1 \tan \phi})^2 - \frac{3C}{\gamma H_1 \tan \phi} + 3 \right] - 36H_1 \quad (24)$$

Where $l_{倾}$ is the inclination span of the arch structure for unconsolidated layer,[m]; $H_1$ is the overburden...
thickness when the arch reaches the limit height of the unconsolidated layer, [m].

Fig.8 Schematic diagram of arch structure development

3 Dynamic evolution law of unconsolidated layer arch structure

3.1 The establishment of numerical model

Taking ShendongHaragou coal mine as research background, the dynamic evolution law of unconsolidated layer arch was analyzed by using UDEC numerical software. The corresponding length and height of numerical model is 100m × 60 m, as shown in Fig.9. Physical and mechanical parameters of rock layer are shown in Table 1.

Table 1 Mechanical parameters of rock mass and joints

| Lithology          | Thickness (m) | Density (kg/m³) | Bulk modulus (GPa) | Shear modulus (GPa) | Tensile strength (MPa) | Cohesion (MPa) | Internal friction angle (°) |
|--------------------|---------------|-----------------|--------------------|---------------------|------------------------|----------------|----------------------------|
| Unconsolidated layer | 40            | 1850            | 10.2               | 4.72                | 0.2                    | 0.027          | 25                         |
| Main roof          | 8             | 2650            | 21.4               | 10.1                | 2.64                   | 2.9            | 34                         |
| Immediate roof     | 5             | 2490            | 10.2               | 4.45                | 0.96                   | 2.5            | 45                         |
| Coal seam          | 5             | 1430            | 8.4                | 4.1                 | 0.73                   | 2.18           | 29                         |
| Immediate floor    | 5             | 2700            | 9.6                | 9.9                 | 2.42                   | 2.6            | 27                         |

3.2 Result and analysis

(1) After coal seam is mined, the immediate roof collapsed primarily. Then the main roof is separated, broken and collapsed. In the process of rock strata movement, uneven displacement occurs between the unconsolidated layers and then forms the "arch shell" structure. It carries the upper loading, while the lower sand layer has broken down.
(2) As the working face advances, the first periodic weighting of the main roof occurs, the bedrock block rotates to form the stepped voussoir beam structure. After the arch foot of the unconsolidated layer collapsed, the separated zone for arch-shaped is filled with the gob. The unconsolidated layer arches upward based on the fracture location of the key layer, and then forms a new "arch shell" structure. This arch structure of unconsolidated layer appears repeatedly until the failure height of overburden reaches the maximum value.
(3) With the advance of working face, the unconsolidated layer arch continues to develop upward. When the thickness of the unconsolidated layer is less than the sum of the theoretical arch height and half of arch thickness for the unconsolidated layer, namely $\sum H < (h + \delta/2)$, the unconsolidated layer arch cannot be formed. But if the strength of surface sandy soil layer is low, when the unconsolidated layer arch develops to a certain height, the upper part of the overlying unconsolidated layer is "beam" while the lower part is "arch", as shown in Fig. 12 (a) and Fig. 12 (b). After the arch beam has fractured, "funnel-shaped" subsidence occurs in the unconsolidated layer, as shown in Fig. 12 (c). Non-uniform subsidence and movement lead to ground fissures appearing at outside of the gob boundary, as shown in Fig. 12 (d).
4 Structure classification of unconsolidated layer for shallow burial coal seam

According to the thickness of the unconsolidated layer for shallow burial coal seam, the structure of unconsolidated layer is classified:

(1) The type of loading: When \( \sum H < h_{\text{min}} + \frac{\delta}{2} \), the arch structure of the unconsolidated layer cannot be formed, the unconsolidated layer acts as the loader on the key strata. \( h_{\text{min}} \) is the arch height of the arch structure for unconsolidated layer when the working face has first initial weighting.

(2) The type of arch-beam broken: When \( h_{\text{min}} + \frac{\delta}{2} \leq \sum H < \sum H_{\text{limit}} \), the arch structure of unconsolidated layer can be formed. And with the advance of the working face, it develops upward. When \( h + \frac{\delta}{2} \geq \sum H \), the bearing structure is no longer formed. And when the unconsolidated layer develops to a certain height, the upper part of the overlying unconsolidated layer is "beam", and the lower part is "arch".

(3) The type of ultimate arched: When \( \sum H > \sum H_{\text{limit}} \), after the arch structure of the unconsolidated layer is formed and reaches the maximum height, it will not develop upward, the structure of unconsolidated layer extends forward in the way of "tunnel".

5 Prediction and analysis of ground fissures

Before the formation of ground fissures, the "arch beam" is in the state of self-stable. The stress analysis of the right side for the arch structure is shown in Fig.13. The top position of arch is point B, the foot of arch is point C, \( \rho \) is the density of sandy soil, \( g \) is the gravitational acceleration. The equation of the catenary arch is \( f(x) = -Hch\sqrt{\frac{y}{FH}} \), the distance between the arch top and ground surface is \( H \).

The stress distribution inside the beam\(^{[11]}\) is:

\[
\begin{align*}
\sigma_x &= -\frac{\rho gx}{f'(x)} + \frac{\rho gxy}{f(x)f'(x)} + \frac{\rho gy}{f^{12}(x)} \\
\sigma_y &= \rho gy \\
\tau_{xy} &= \frac{\rho gy}{f'(x)} 
\end{align*}
\]

The maximum normal stress \( \sigma_{\text{max}} \) in the beam is:

\[
\sigma_{\text{max}} = (\mu + \sqrt{\mu^2 + sxy(1 - t)})\rho g
\]

where \( \mu = \frac{s^2y + sx + sxt + y}{2} \), \( s = \frac{1}{f'(x)} = -\frac{1}{H\sqrt{\frac{\gamma}{FH}}sh\sqrt{\frac{\gamma}{FH}}} \), \( t = \frac{y}{f(x)} = -\frac{y}{Hch\sqrt{\frac{\gamma}{FH}}} \).
When the upper boundary $y=0$ and $\frac{\partial \sigma_{max}}{\partial x} = 0$, it reaches the maximum value $\sigma_{max}$.

When $x = \frac{l}{2 \text{arcch} \left( \frac{H + h}{H} \right)}$, $\sigma_{max} = \frac{\rho g l^2}{6.17H \text{arcch}^2 \left( \frac{H + h}{H} \right)}$ (26)

The ultimate tensile strength of the unconsolidated layer is $[\sigma]$, then

1. When $\sigma_{max} < [\sigma]$, there is no ground fissures in the upper boundary of the "arch-beam" structure;
2. When $\sigma_{max} \geq [\sigma]$, there is tensile-type ground fissure in the upper boundary of the "arch-beam" structure.

The span of the arch-beam is:

$$l = \sqrt{\frac{6.17[\sigma]H \text{arcch}^2 \left( \frac{H + h}{H} \right)}{\rho g}}$$

The corresponding advanced distance of working face $L$ is:

$$L = \sqrt{\frac{6.17[\sigma]H \text{arcch}^2 \left( \frac{H + h}{H} \right)}{\rho g}} + 2 M \cdot \cot \alpha$$

6 Engineering verification

The measured results of ground fissures distribution caused by 22207 working face mining under the condition of thick unconsolidated layer for Shengdong Halagou Coal Mine were selected to verify the influence of the arch structure on surface damage. The striking length and the tendency length of 22207 working face is 4597.5 m and 305 m respectively, the average thickness of coal seam is 5.5 m, the dip angle is 1~3°. The average burial depth is 60 m, the bedrock is 20 m and the unconsolidated layer is 40 m. The advancing speed of 22207 working face is approximately 12.1 m/d. The immediate roof consists of siltstone and medium sandstone, the thickness is 3.2 m and 2.8 m respectively. The main roof is fine sandstone and its thickness is 10.3 m. The distance of first weighting is about 30 m, the distance of periodic weighting is about 14 m.

![Fig.14 Column diagram of 2-2 coal seam](image)

The parameters of Halagou coal mine are as follows: the bulk density of the unconsolidated layer is 18.5 kN/m$^3$, the cohesion $C$ is 27 kPa, the internal friction angle $\phi$ is 25°, density $\rho$ is 1.850 g/cm$^3$, tensile strength $\sigma$ is 0.2 MPa. These above parameters are substituted into Equations (16) and (26). The dynamic evolution of the arch structure for unconsolidated layer and its influence on the ground fissures are analyzed, as shown in Fig.15.
### Table 2 Judgment result of ground fissures generation

| The weighting condition of main roof | Advanced distance (m) | The span of unconsolidated layer (m) | The height of arch structure (m) | The thickness of arch structure (m) | Determination of ground fissures generation | $\sigma_{\text{max}}$ (kPa) |
|-------------------------------------|-----------------------|-------------------------------------|---------------------------------|-----------------------------------|--------------------------------------------|------------------|
| First weighting                     | 30                    | 24.4                                | 11.2                            | 3.7                               | No                                         | 84.7             |
| Periodic weighting                  | First time            | 44                                  | 38.4                            | 16.1                              | No                                         | 151.8            |
|                                    | Second time           | 58                                  | 52.4                            | 20.7                              | Yes                                        | 231.4            |

It can be seen from Table 2 and Fig.15, when the second periodic weighting occurs in Halagou Coal Mine 22207 working face, the unconsolidated layer presents the failure type of "arch-beam". Then the ground fissure appears. The advanced distance of 22207 working face is 58 m at the moment. See Fig.16, Through geology investigation of the ground surface for 22207 working face, it is found that a series of collapsed fissures have formed, which is consistent with the theoretical analysis.

![Fig.15 Ground fissures of Halagou Coal Mine](image)

### 7 Conclusion

1. The mechanical model of the arch structure for thick unconsolidated layer under the condition of shallow burial coal seam is established. As the span of arch structure increases, the height of arch structure increases nonlinearly. The greater the thickness of the unconsolidated layer, the greater the ultimate arch height and the ultimate arch span.

2. The dynamic evolution mechanism of the arch structure for the unconsolidated layer is revealed. During the mining process, the structure of unconsolidated layer develops in the shape of "arch" from the bottom to the top. The "arch-beam" failure type is formed with "beam" at the top and "arch" at the bottom. The formulas for calculating the minimum height and ultimate height of the arch structure are obtained.

3. The influence mechanism of arch structure on ground fissures is revealed, and the calculation formula of working face advanced distance when ground fissure appears for the first time is obtained:

$$ L = \left[ \frac{6.17 \rho H \tan^2 \arccos \left( \frac{H + h}{H} \right)}{\rho \sigma} \right] + 2 \sum M \cdot \cot \alpha $$

4. According to different thickness of the unconsolidated layer, the arch structure of the unconsolidated layer is divided into three types:
   1. The type of loading: the bearing structure fails to form, and the unconsolidated layer acts on the bedrock as the load;
   2. The type of arch-beam broken: the bearing structure is formed inside the unconsolidated layer, it finally failure as the type of "arch-beam" with the advance of the working face;
   3. The type of ultimate arched: the arch structure is formed inside the unconsolidated layer, and the arch height will not change when it reaches the ultimate value.

**Data availability statement**

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.
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