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Research Article

Evolution Mechanism of Thickly Sticky Loose Layered Arch Structure and Prediction Method of Initial Ground Fissure Caused by Underground Coal Mining

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In view of the problem of taking the loose layer as the uniform cloth load while ignoring thickly sticky loose layered arch (TSLLA) of the traditional mining rock overburden structure analysis, combined with the geological conditions of shallow buried thickly sticky loose layer in Shendong mining area, the mechanical model of the mining TSLLA bearing structure is established, the variation law of arch height under different loose layers is analyzed, and the formation conditions of TSLLA are given. The first theory deduced the dynamic evolution mechanism of TSLLA structure advancing. The dynamic evolution of TSLLA structure in 22207 coalface is simulated. The formula for the limit height of TSLLA is derived. A classification method of mining loose layer structure is proposed. The loose layer structure type is divided into load type, arch beam type damage type, and limit arch height type. On this basis, the mechanical model of "arch beam" is constructed. The influence mechanism of the TSLLA on the surface cracks is revealed. The methods and calculation steps for initial surface cracks are presented. The results are verified by the measured data of surface subsidence of the typical thickly sticky layer in Shendong mining area.

1. Introduction

Mine pressure and rock stratum control are one of the important directions in the field of coal mining research, which directly affects underground production safety and surface ecological restoration. During the long-term research process, numerous hypotheses and structural models have been formed in the field of mine pressure and rock stratum control, such as "masonry beam," "transfer rock beam," "cantilever beam," and "key stratum layer theory" [1–3]. The abovementioned theories simplify the loose layers as a uniformly distributed load acting on the main roof of bedrock and ignores the bearing structure in the loose layer [4, 5]. It is found that during the mining process of shallow buried coal seam, the weight of collapse of thick loose layer (mainly clayey loose layer) is not instantaneously applied to the main roof of bedrock, and there is "loose layer arch" bearing structure [6]. For this reason, the thick loose layer of shallow buried coal seam has "arch" effect by similar simulation test, the height of unloading "arch" during the initial pressure by using Pratt's arch mechanics model was determined [7], the criterion of rupture of thick sandy soil layer and the location of tension crack was gave, and the stress arch mechanics model with thin bedrock and thick loose layer, and obtained the relationship between stress arch span and arch height was established [8–10]. Wang established the structural mechanics model of loose layer arch, revealed the morphology equation, vector-span ratio equation, and thickness equation of loose layer arch, and obtained the theoretical expression of critical loose layer thickness that can form loose layer arch [11]. Zuo et al. constructed a

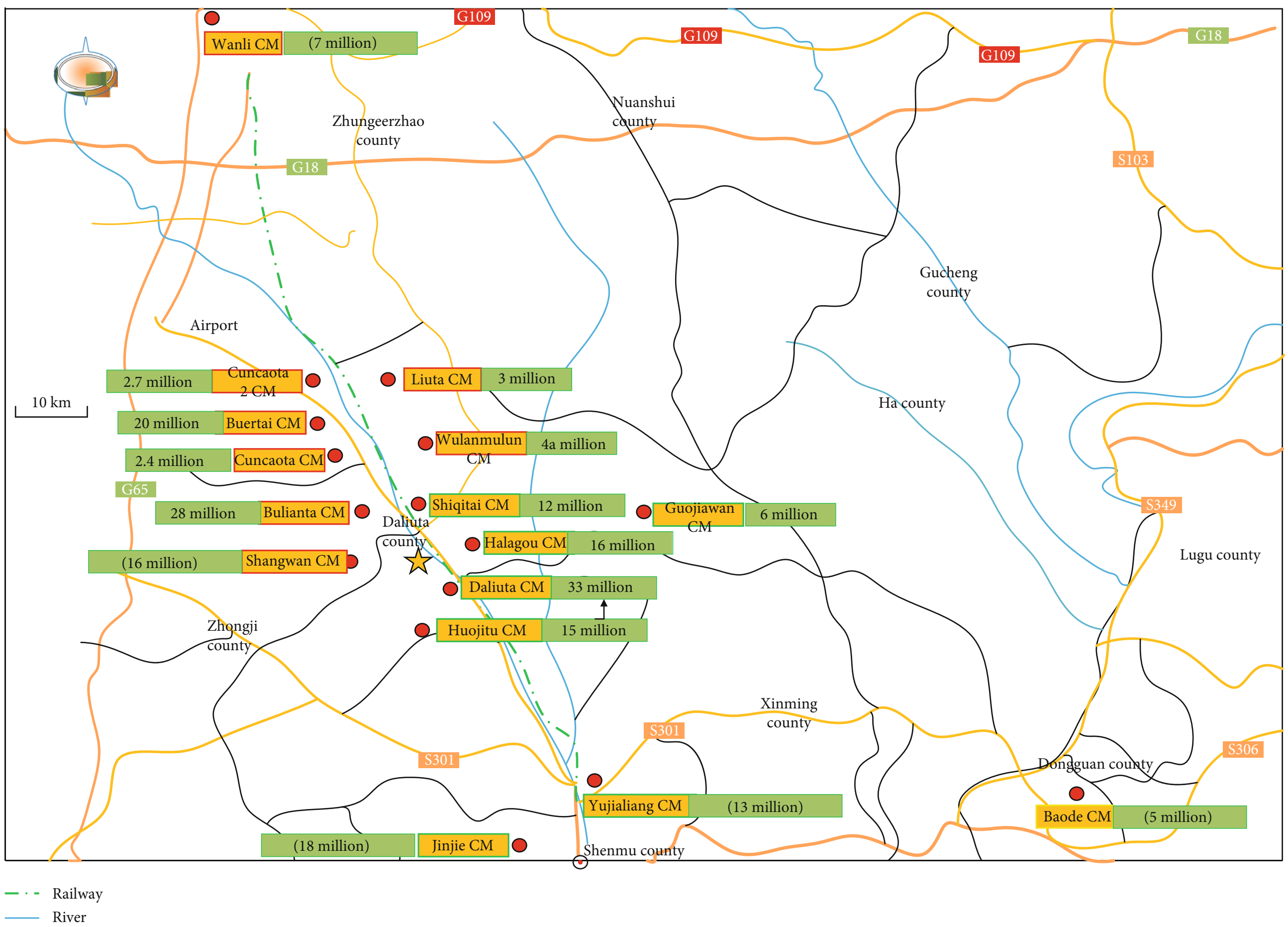


Figure 1: Location of Shendong mining area.

"hyperbolic-like" model for thick loose layer overburden and derived a formula for calculating the extent of surface subsidence [12, 13]. Li et al. put forward the mechanical model of "layer double arch" bearing structure and make the stress analysis of "layer double arch" bearing structure under the analysis formula of its ultimate bearing strength [14]. Wang et al. put forward the theory of stress bearing arch strength such as anchor cable in deep soft rock roadway and also deduce the bearing capacity formula of circular bearing arch [15]. Xue et al. explored the fracturing evolution process and energy driving mechanism of coal seam and then played a guiding role in the prediction of rock instability and the selection of support and reinforcement measures [16, 17].

The existing research results have promoted the development of the loose layer arch model, but the existing research mainly focuses on the formation mechanism and breakage conditions of static arch, but rarely involves the dynamic development characteristics of the loose layer arch during the mining process [18–25]. Additionally, the overburden load on the loose layer arch is simplified to the uniform load, which has certain limitations. In turn, the mining evolution characteristics of the loose layer arch directly determine the surface fracture development pattern and rock load change characteristics.

On the basis, the research simplifies the thickly sticky loose layer arch (TSLLA) structure into a three-hinged arch mechanical model under the action of fill pressure, derives the morphological equation, thickness equation, and the relationship equation between arch height and span of the loose layer arch, and reveals the dynamic evolution mechanism of the TSLLA bearing structure during coal mining. The structure of mining-induced loose layer is divided into three types according to the thickness of loose layer, and the prediction method and steps of the initial ground fissures are put forward. Furthermore, the predicted results are verified by the measured data.

2. Materials and Methods

2.1. Study Site. Shendong mining area is the largest coal production base in China, including 19 coal mines (Figure 1). It crosses the junction of Shaanxi, Inner Mongolia, and Shanxi and belongs to an arid and semiarid area, with an average rainfall of 396.8 mm and an annual evaporation of 2772 mm. The output of coal accounts for about 6% of the country's total output [26, 27].

No.	Thickness (m)	Buried depth (m)	Lithology
9	40.6	40.6	Aeolian sand layer
8	1.7	42.3	Coarse sandstone
7	2.1	44.4	Sandy mudstone
6	10.3	54.7	Fine sandstone
5	2.8	57.5	Medium sandstone
4	3.2	60.7	Siltstone
3	5.5	66.2	2^{-2} coal
2	6.3	72.5	Sand mudstone
1	15.0	87.5	Fine sandstone

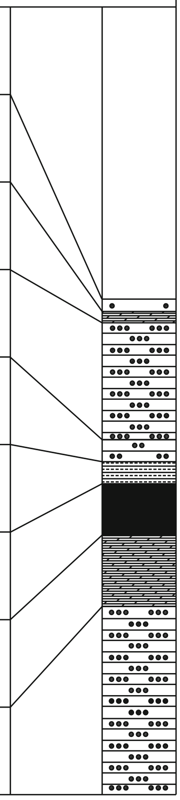


FIGURE 2: Borehole histogram of 22207 coalface.

Taking the 22207 coalface of Halagou coal mine in Shendong mining area as an example, 22207 coalface mines 2-2 coal seam with a strike length of 4597.5 m and a tendency length of 305 m. The average thickness of the coal seam is 5.5 m, the dip angle of the coal seam is 1 ~ 3°, and the average burial depth is 60 m. The thickness of the bedrock is 20 m, and the thickness of the loose layer is 40 m. The workings are retrieved at a rate of about 12.1 m/d. The direct top is 3.2 m siltstone and 2.8 m medium sandstone, and the basic top is 10.3 m fine sandstone in 22207 coalface. The drill hole column of the 22207 coalface is shown in Figure 2.

2.2. Methodology

2.2.1. Research Process. The research in this paper is mainly divided into two parts: evolution mechanism of TSLLA structure and prediction method of initial ground fissure caused by underground coal mining. Then, the calculation results are verified through the surface settlement measurement data of the typical thick adhesive layer of the 22207 coalface in Shendong mining area.

2.2.2. Introduction for TSLLA Bearing Structure. The cohesive force and internal friction force between particles in the viscous loose layer have high shear strength, which is easy to meet the conditions of Terzaghi soil arching effect. In the coal mining process, the soil arch effect is easily formed in the clayey loose layer. After the mining of shallow buried coalface, the mining-included overburden structure breaks and destabilizes and gradually develops upward to the loose layer, the internal medium of the loose layer is deformed, uneven displacement occurs between the particles, the force transfer between the lower loose layer and the overlying loose layer disappears and disengages, and a curve or a folding line is formed in the particles of the overlying loose layer that mainly bears axial compressive stress and sometimes can also bear bending moment while transferring thrust to both sides of the support rod-shaped structure [11]. This kind of load-bearing structure can transfer load between particles in different areas of the loose layer and can play a bearing role on the mining overburden, and at the same time, can play a protective role on the quarry is the loose layer arch structure. The loose layer arch structure mainly consists of the arch body of the loose layer arch structure and the support at the base of the arch. The arch body of the loose layer arch structure mainly bears the axial compressive stress, while the support at the base of the arch can simultaneously bear the vertical compressive stress, horizontal thrust, and bending moment. The overburden bearing structure under coal mining is shown in Figure 3, of which the bearing structure in the bedrock is the key layer structure, and the bearing structure in the loose layer is the loose layer arch structure.

2.2.3. Bearing Structure Mechanical Model of TSLLA. The bearing structure of thickly sticky loose layer arch (TSLLA) structure is properly simplified, and the mechanical model is constructed. The simplified assumptions are as follows:

(1) The thickness of the loose layer arch is kept consistent from the top of the arch to the arch base, and the reasonable arch axis of the loose layer arch is studied by analyzing the midplane curve

(2) The loose layer arch structure is simplified to a three-hinged arch, i.e., the reasonable arch axis of the three-hinged arch is used as the reasonable arch axis of the loose layer arch structure

(3) The fill on the loose layer arch is loaded by the weight of the fill

(4) In view of the shallowly buried coal seam, the horizontal stress is assumed to be zero

A rectangular coordinate system is established with the vault as the origin, as shown in Figure 4. The distance from the arch top to the surface is the thickness of the overburden loose layer, H; the arch height is expressed by h; the arch span is expressed by l; the loose layer arch is subjected to the fill load $q(x) = \gamma(H + y)$, and γ is the bulk density of loose layer, N/m^3.

2.2.4. Characteristic Equation of Loose Layer Arch Structure. The general expression of reasonable arch axis equation of

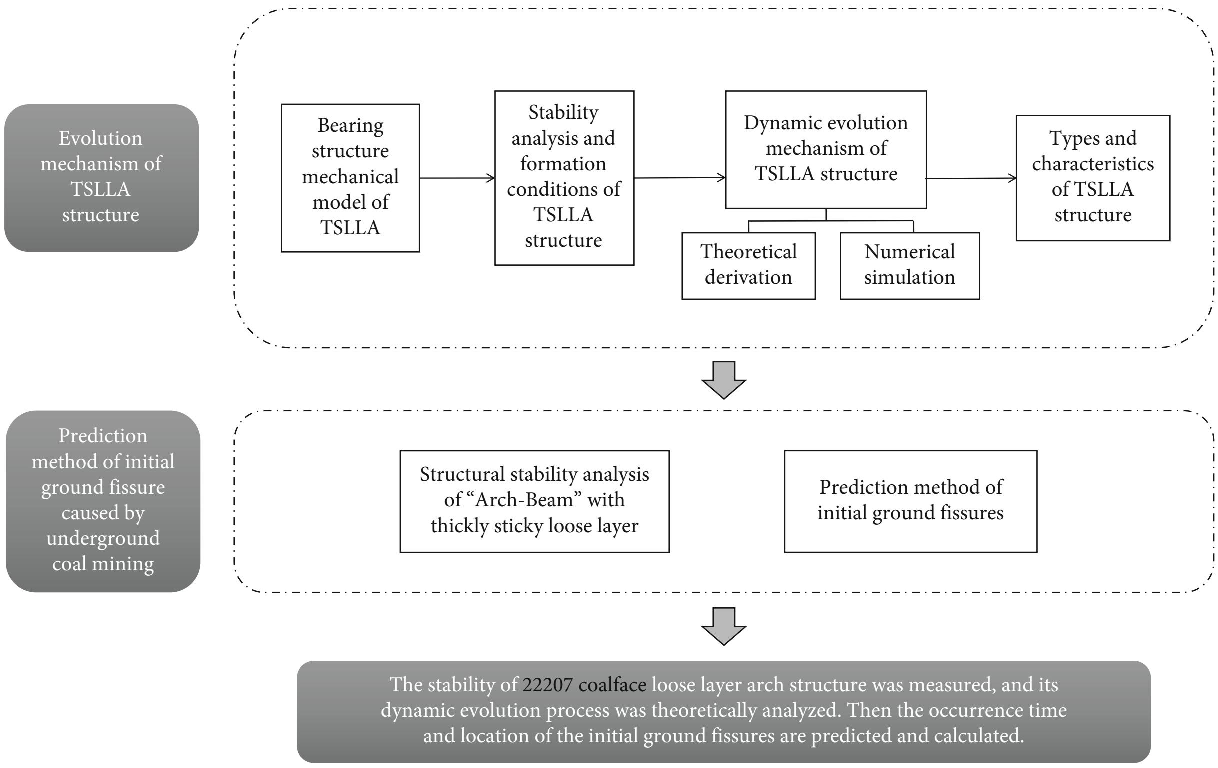


Figure 3: Research flow chart.

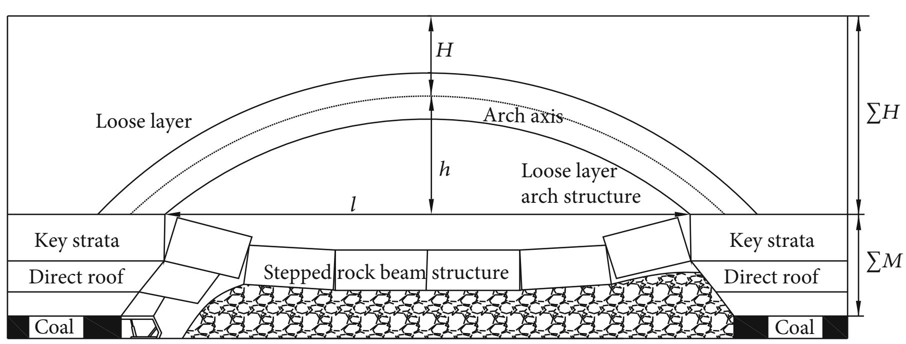


Figure 4: Bearing structure in the overlying strata.

three hinged arch is

$$y = \frac{M^0(x)}{F_H}, \tag{1}$$

where $M^0(x)$ is the bending moment of simply supported beam under filling load, kN·m; F_H is the horizontal support reaction force, kN.

Taking the second order derivative of both sides of Formula (1) yields

$$y'' = \frac{1}{F_H}\frac{d^2M^0}{dx^2}. \tag{2}$$

The equilibrium differential equations of straight bar microsegments are approximated $d^2M^0/dx^2 = -q(x)$, Formula (2) is

$$y'' = \frac{d^2y}{dx^2} = -\frac{q(x)}{F_H}. \tag{3}$$

Formula (3) specifies that y-axis is positive upward, then

$$\frac{d^2y}{dx^2} = \frac{q(x)}{F_H}. \tag{4}$$

$q(x) = \gamma(H + y)$ is substituted into Formula (4), then

$$\frac{d^2y}{dx^2} - \frac{\gamma}{F_H}y = \frac{\gamma H}{F_H}. \tag{5}$$

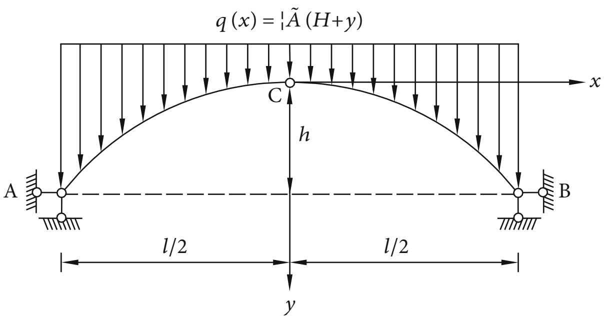


Figure 5: Mechanical model of TSLLA structure.

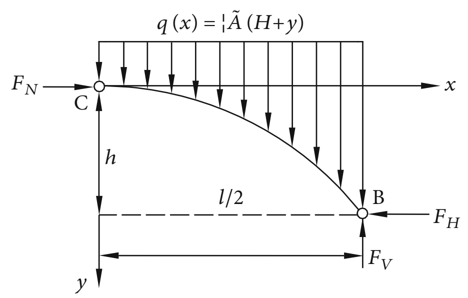


Figure 6: Mechanical analysis chart of arch structure.

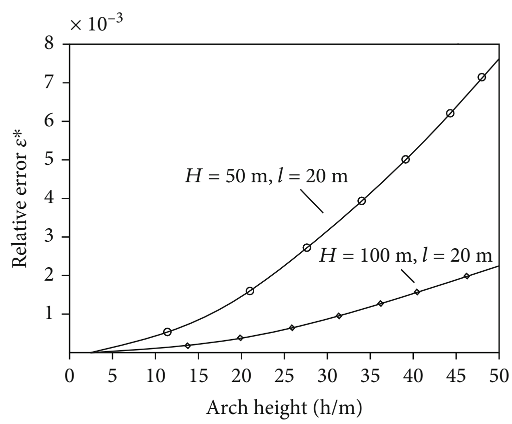


Figure 7: Relationship lines between ε^* and h.

The general solution of the differential equation can be expressed as a hyperbolic function:

$$y = \mathrm{A}\mathrm{ch}\sqrt{\frac{\gamma}{F_H}}x + B\mathrm{sh}\sqrt{\frac{\gamma}{F_H}}x - H. \tag{6}$$

From the boundary conditions:

when $x = 0$, $y = 0$, and $A = H$; when $x = 0$, $y' = 0$, and $B = 0$.

Thus, the reasonable arch axis equation is obtained as below.

$$y = H\left[ch\sqrt{\frac{\gamma}{F_H}}x - 1\right]. \tag{7}$$

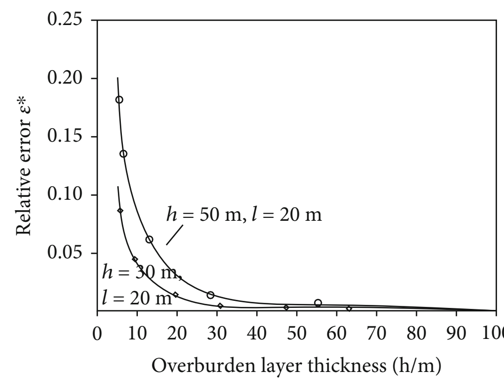


Figure 8: Relationship lines between ε^* and H

That is, the reasonable axis of the three-hinged arch is a catenary under the action of the weight of the fill.

2.2.5. Mechanical Model of Loose Arch Structure. The stress analysis of the right arch of the loose layer arch structure is shown in Figure 5.

The load of the overlying fill on the loose layer arch is $q(x) = \gamma H \mathrm{ch}\sqrt{(\gamma/F_H)}x$, let $m = \sqrt{\gamma/F_H}$, then, horizontal support reaction is obtained.

$$F_H = \frac{\gamma}{m^2}. \tag{8}$$

According to the vertical equilibrium equation $\sum F_y = 0$, that is, $\int_0^{l/2} q(x)dx - F_V = 0$, we get

$$F_V = \frac{\gamma H}{m}\mathrm{sh}\left(\frac{ml}{2}\right). \tag{9}$$

From the bending moment equilibrium equation of hinge point $C \sum M_C = 0$, we get

$$F_H \times h = F_V \times \frac{l}{2} - \int_0^{l/2} q(x)x dx. \tag{10}$$

Formulas (8) and (9) are substituted into Formula (10).

$$h = H\mathrm{ch}\left(\frac{ml}{2}\right) - H. \tag{11}$$

Taylor's expansion for hyperbolic functions:

$$\mathrm{sh}x = x + \frac{x^3}{6}, \mathrm{ch}x = 1 + \frac{x^2}{2} + \frac{x^4}{24}. \tag{12}$$

Then, Formula (11) is simplified to

$$m^4 l^4 + 2Hm^2 l^2 - 16h = 0. \tag{13}$$

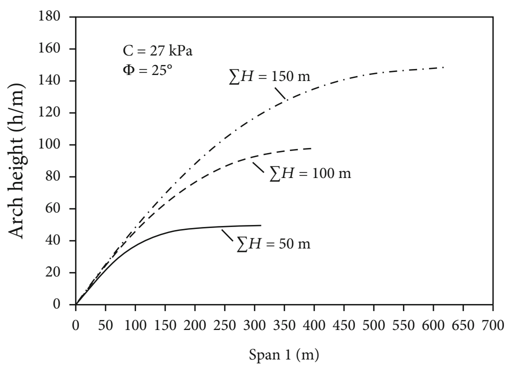


FIGURE 9: Variation of h with l under different loose layer thicknesses.

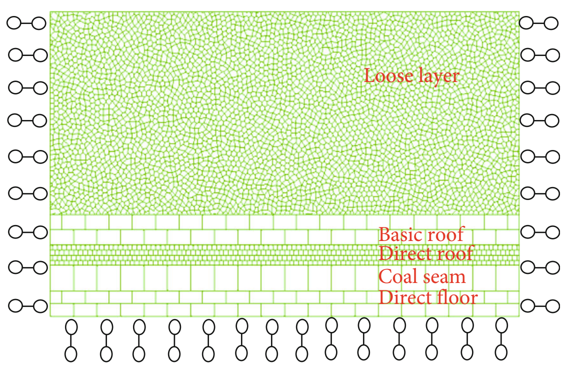


FIGURE 10: Numerical model for the evolution law of arch structure.

We get

$$m = \frac{2}{l}\sqrt{\sqrt{\frac{24h}{H} + 36} - 6}. \tag{14}$$

Then, the relative error ε^* is expressed as

$$\varepsilon^* = \frac{h\text{-}h^*}{h} = \frac{h\text{-}H\text{ch}(ml/2) + H}{h}. \tag{15}$$

The relative error ε^* varies with parameters h and H, as shown in Figures 6 and 7.

(1) The relative error ε^* with the arch height h increases and decreases with increasing overburden layer thickness H

(2) When h and H change within a certain range, and the relative error $\varepsilon^* < <1$, Formula (12) was established

Formula (12) is substituted into Formulas (8) and (9), and the simplification can be obtained.

$$F_H = \frac{\gamma l^2}{4\sqrt{(24h/H) + 36} - 24}, \tag{16}$$

$$F_V = \frac{\gamma H l}{12}\sqrt{\frac{24h}{H} + 36}. \tag{17}$$

3. Stability Analysis and Formation Conditions of TSLLA Structure

3.1. Stability Analysis of Loose Layer Arch Structure. According to [28] research results on loose layer arch, the conditions for the stability of loose layer arch structure are as follows:

$$F_H \le F_V \tan\varphi + \frac{1}{2}Cl, \tag{18}$$

where φ is the internal friction angle of the loose layer, °; C is cohesion of loose layer, Pa.

Formulas (16) and (17) are substituted into Formula (18), and it can be obtained that the arch height h of the loose layer in the limit state is

$$h = \frac{H\left[\sqrt{(3l/H\tan\varphi) + (3 + (3C/\gamma H\tan\varphi))^2} - (3C/\gamma H\tan\varphi) + 3\right]^2 - 36H}{24}. \tag{19}$$

Let loose layer thickness $\sum H = H + h$, then, the span l of loose layer in the limit state is

$$l = \left(\frac{\tan\varphi}{3}\sqrt{\left(36\sum H - 12h\right)\left(\sum H - h\right)} + \frac{2C}{\gamma}\right) \times \left(\sqrt{\frac{36\sum H - 12h}{\sum H - h}} - 6\right). \tag{20}$$

Figure 8 shows that with the increase of span l, the arch height H of loose layer in the limit state increases nonlinearly, and the increase is decreasing gradually. The greater the thickness of the loose layer $\sum H$, the greater the ultimate arch height h and the ultimate span l of the loose layer arch.

3.2. Formation Condition of Loose Layer Arch Structure. In order to facilitate the calculation, the loose layer arch structure is simplified as a reasonable arch axis, but the loose layer arch structure has a certain thickness, so the formation condition of the loose arch structure is given by considering the thickness of the loose layer arch.

According to the More Coulomb strength criterion, to form a loose-layer arch with stable load-bearing action, the maximum and minimum principal stresses at the arch base should satisfy

$$\sigma_1 = \sigma_3 \tan^2\left(\frac{\pi}{4} + \frac{\varphi}{2}\right) + 2C\tan\left(\frac{\pi}{4} + \frac{\varphi}{2}\right), \tag{21}$$

Table 1: Mechanical parameters of rock mass and joints.

Strata	Layer thickness/m	Physical and mechanical parameters of rock formations Density/kg/m^{-3}	Bulk modulus/ GPa	Shear modulus/ GPa	Tensile strength/ MPa	Internal cohesion/ MPa	Internal friction angle/°
Loose layer	40	1850	10.2	4.72	0	0.085	25
Basic top	10	2650	21.4	10.1	2.64	2.9	34
Direct top	5	2490	10.2	4.45	0.96	2.5	45
Coal	5	1430	8.4	4.1	0.73	2.18	29
Direct bottom	5	2700	9.6	9.9	2.42	2.6	27

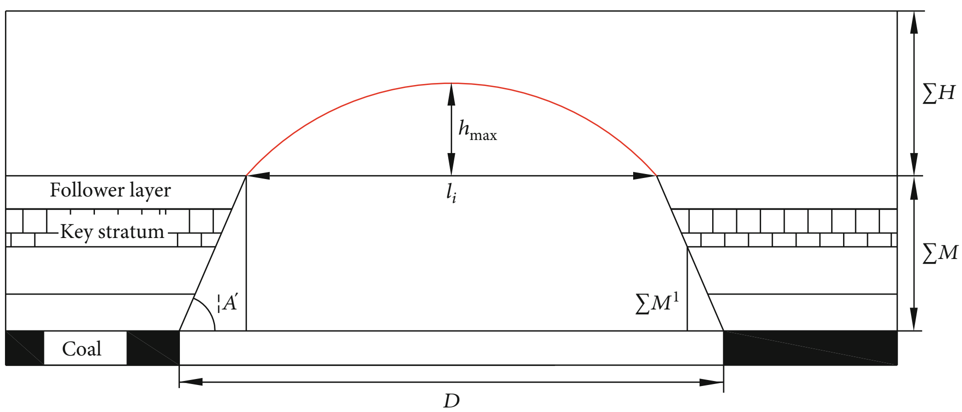


Figure 11: Calculation diagram of l.

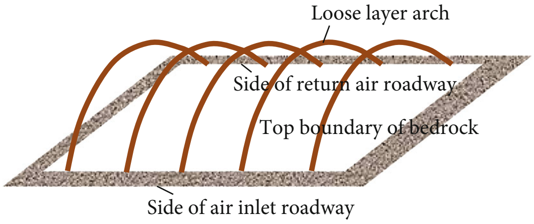


Figure 12: Schematic diagram of arch structure development.

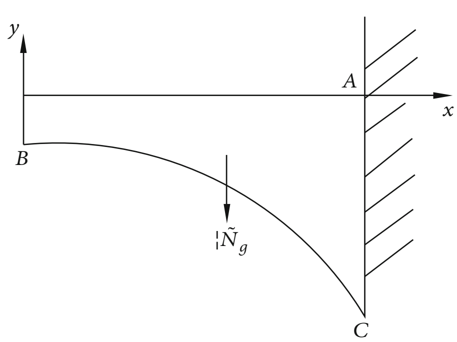


Figure 13: Mechanical analysis chart of arch beam structure.

where σ_1 and σ_3 are the maximum principal stress and minimum principal stress, respectively.

Through theoretical analysis, the maximum and minimum ultimate principal stresses at the loose layer arch foundation are as follows:

$$\begin{cases} \sigma_{1f} = \dfrac{\gamma H l}{2\delta \cos \varphi}, \\ \sigma_{3f} = \gamma(h + H), \end{cases} \tag{22}$$

where σ_{1f} and σ_{3f} are, respectively, the maximum and minimum ultimate principal stresses at the arch foundation of loose layer; δ is the arch thickness of loose layer.

Formula (22) is substituted into Formula (21) to obtain the arch thickness of the loose layer, so,

$$\delta = \frac{\gamma H l}{2 \cos \varphi \tan ((\pi/4) + (\varphi/2))[\gamma(h + H) \tan ((\pi/4) + (\varphi/2)) + 2C]}. \tag{23}$$

As shown in Figure 9, when the thickness of the loose layer $\sum H$ is greater than the sum of the arch height of the loose layer h and the semiarch thickness $\delta/2$, the loose layer is arched; otherwise, no "arch" structure is formed in the loose layer, i.e.,

$$\sum H \geq h + \frac{\delta}{2}. \tag{24}$$

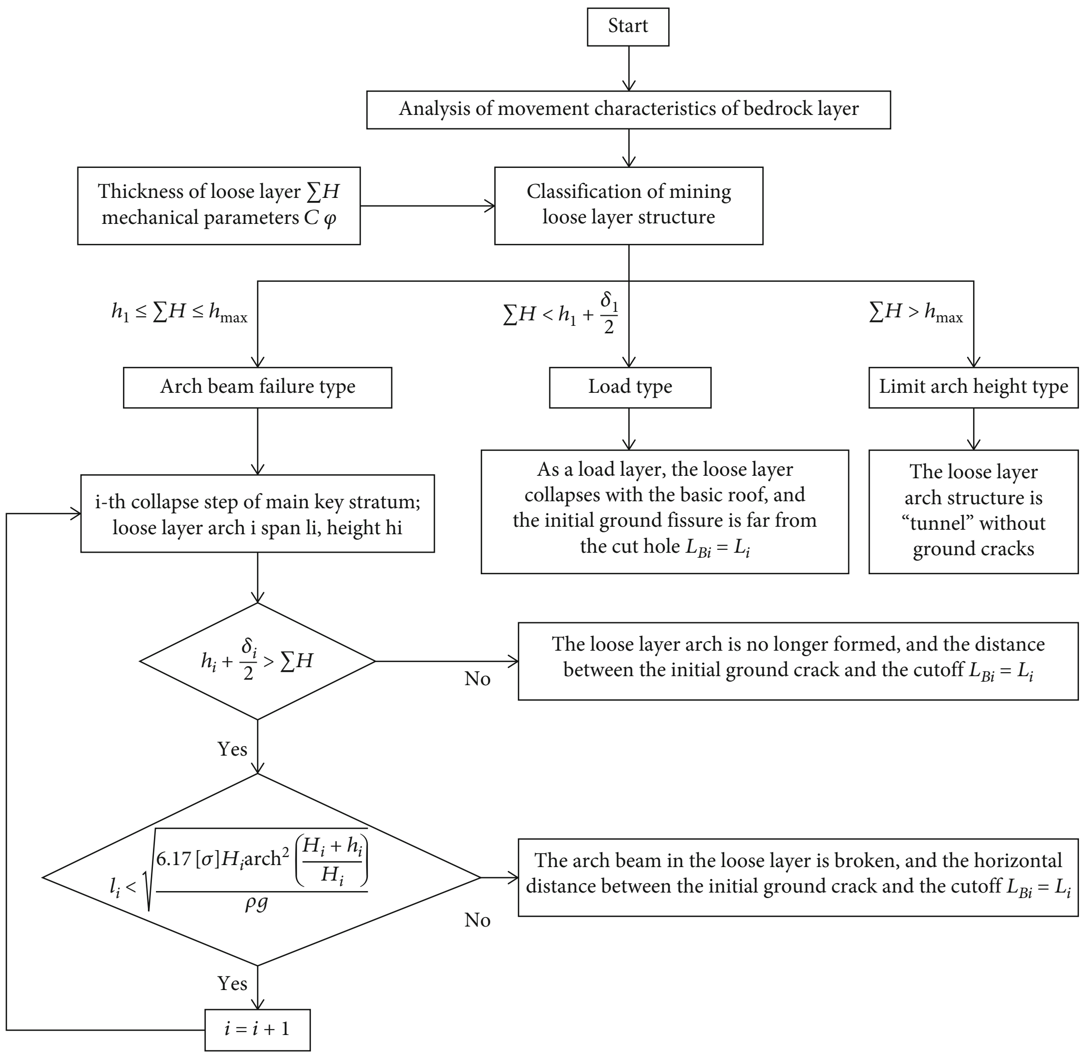


Figure 14: Prediction process for initial ground fissure.

4. Dynamic Evolution Mechanism of TSLLA Structure

4.1. Theoretical Derivation of Dynamic Evolution Law of Loose Layer Arch Structure. Under shallow buried thin bedrock mining conditions, with the advancement of coalface and periodic breakage of bedrock layer, the main key layer breaks and destabilizes, the loose layer begins to settle unevenly, the loose layer arch bearing structure is formed for the first time, and the height h_1 of the loose layer arch is

$$h_1 = \frac{H_1\left[\sqrt{(3l_1/H_1 \tan\varphi) + (3 + (3C/\gamma H_1 \tan\varphi))^2} - (3C/\gamma H_1 \tan\varphi) + 3\right]^2 - 36H_1}{24}. \quad (25)$$

Among them,

$$l_1 = L_1 - 2\sum M \cdot \cot\alpha = L_{k1} - 2\left(\sum M - \sum M_1\right) \cdot \cot\alpha, \quad (26)$$

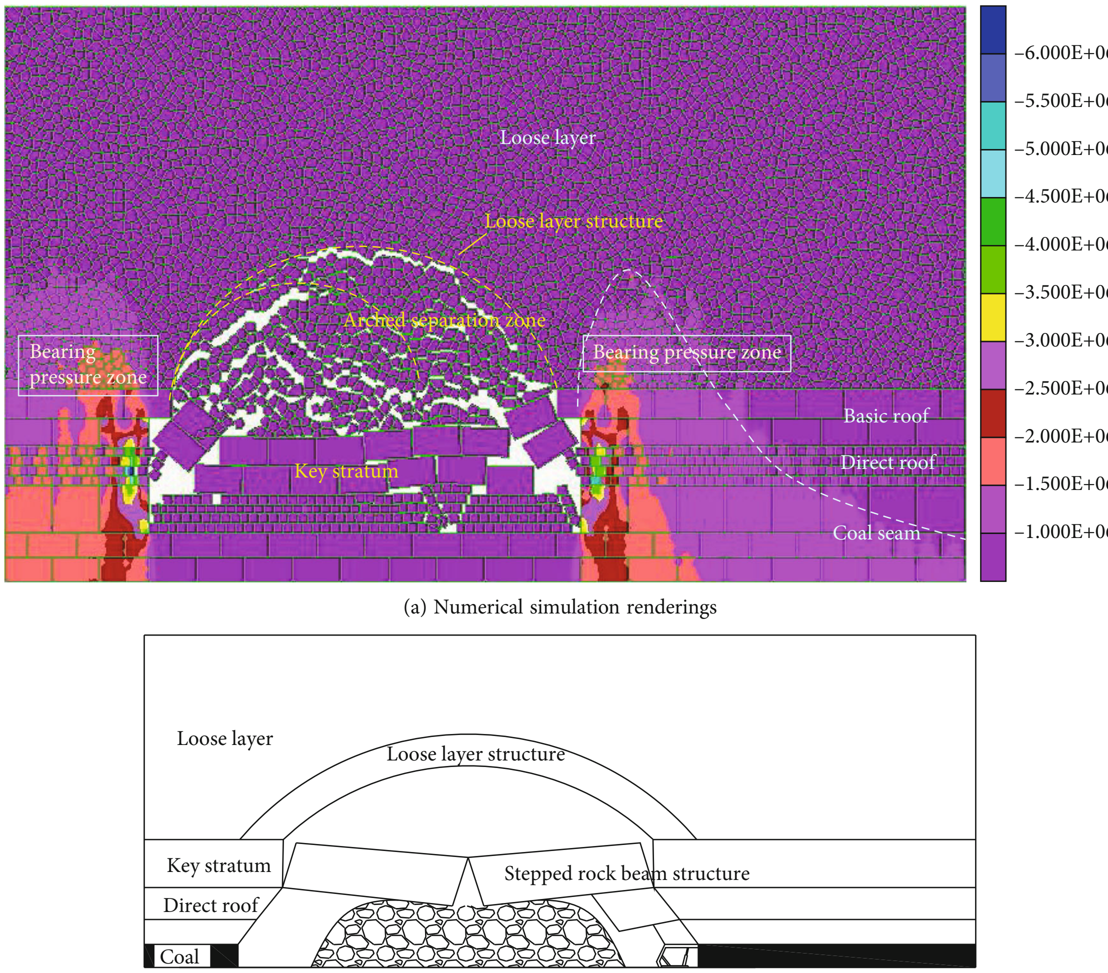
where l_1 span of loose layer arch when the main key layer is first broken, m; $\sum M$ is the thickness of bedrock layer, m; α is the overlying rock breaking angle,°; L_1 is the coalface advance distance when the main key layer is first broken, m; L_{k1} is the initial breaking distance of the main key layer, m; $\sum M_1$ is the height between the main key stratum and the coal seam, m; H_1 is the thickness of overlying rock layer over the loose layer arch when the main key layer is first broken, m.

With the continuous advance of the coalface and the periodic breaking of the main key layer, the loose layer arch bearing structure keeps collapsing and destabilizing and developing upward. During the period, the height h_n of the loose layer arch is

$$h_n = \frac{H_n\left[\sqrt{(3l_n/H_n \tan\varphi) + (3 + (3C/\gamma H_n \tan\varphi))^2} - (3C/\gamma H_n \tan\varphi) + 3\right]^2 - 36H_n}{24}. \quad (27)$$

Among them,

$$l_n = L_n - 2\sum M \cdot \cot\alpha = L_{kn} - 2\left(\sum M - \sum M_1\right) \cdot \cot\alpha, \quad (28)$$



(a) Numerical simulation renderings

(b) Schematic diagram of overburden structure collapse

Figure 15: Schematic diagram of arch structure during the first weighting.

where l_n is the arch span of loose layer when the main key layer breaks for the nth time, m; n is the times of main key stratum failure; L_{kc} is the periodic fracture distance of main key stratum, m; L_{kn} is the nth time failure distance of the main key stratum, m; L_n is the advance distance of coalface when main key stratum breaks for the nth time, m; H_n is the thickness of rock layer overlying the arch of the loose layer when the main key layer is broken for the nth time, m.

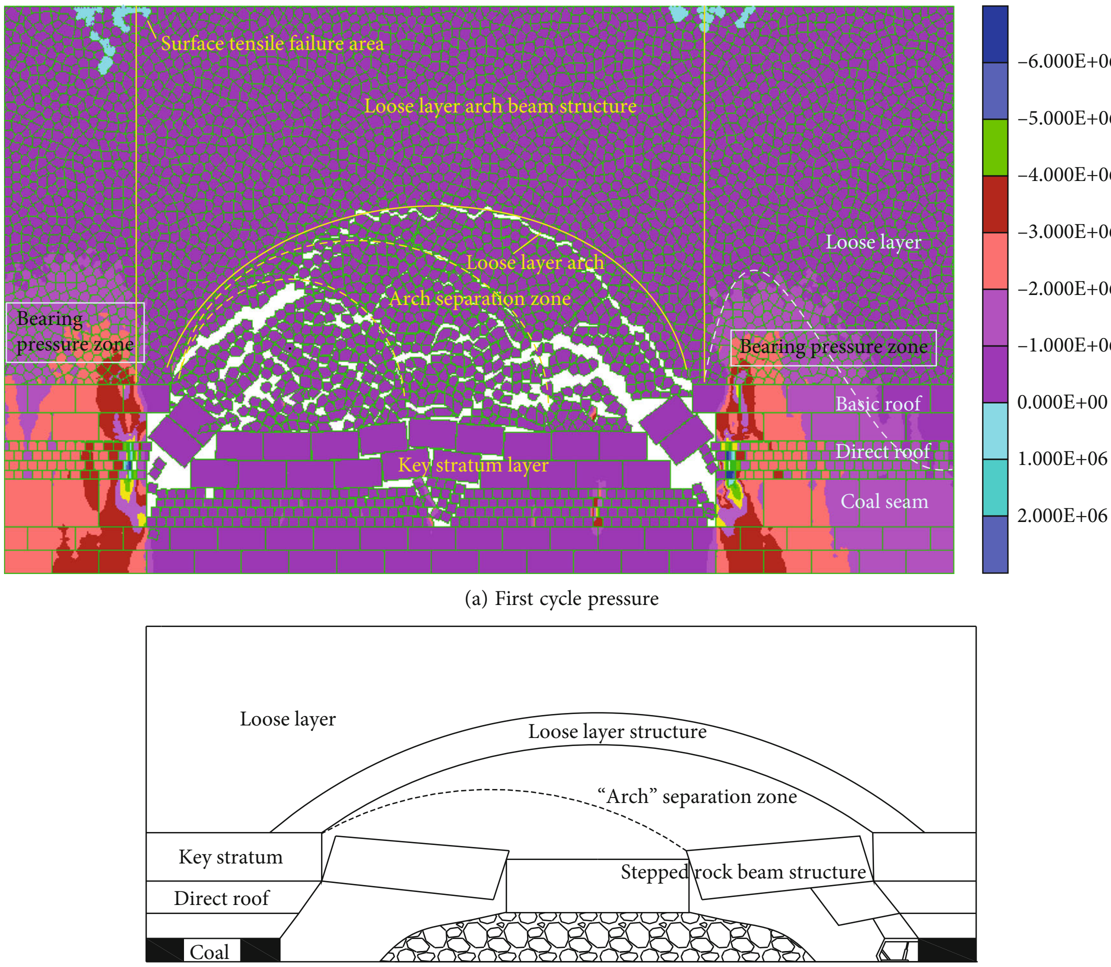
When the arch of the loose layer develops to a certain height, the overlying loose layer will show the "arch beam" type structure with the upper part as "beam" and the lower part as "arch" and will eventually break with the increase of the span of the "arch beam." The "arch beam" span increases and breakage occurs, and mining damage begins to appear on the surface.

4.2. Numerical Simulation of Dynamic Evolution Law of Loose Layer Arch Structure. Taking Shendong Halagou coal mine as the background, the numerical model with Length × Height = 100 m × 60 m is established using UDEC to analyze the dynamic evolution law of the loose layer arch, as shown in Figure 10. The physical and mechanical parameters of the rock formation are shown in Table.1.

5. Types and Characteristics of TSLLA Structure

Under different mining geological conditions, the thickness of the loose layer is an important factor in determining the structure type and movement form of mining rock and soil layer. Therefore, the classification of bearing structure of loose layer based on the thickness of loose layer is of great significance to the study of the movement law of mining rock and soil layer.

5.1. Limit Height of Loose Layer Arch Structure. Under the condition that the thickness of loose layer is very large, with the advance of coalface and the periodic breaking of key layer of bedrock, the loose layer arch bearing structure continuously collapses and destabilizes and develops upward, when the advance distance is much larger than the length of coalface, according to the elastic mechanics plane strain theory [29], the loose layer arch structure reaches the maximum height and no longer develops upward, and the loose layer structure is "tunnel" type forward extension, as shown in Figures 11 and 12. At this time, the inclined span of the



(b) Schematic diagram of overburden structure collapse

FIGURE 16: Schematic diagram of arch structure during periodic weighting.

arch is express as below [30, 31].

$$l_{\text{inclined}} = D - 2\sum M \cdot \cot \alpha, \tag{29}$$

where D is the inclined width of coalface, m.

Assuming that the thickness of rock and soil layer overlying the loose layer tends to be infinite, the limit height of the loose layer arch structure h_{max} is

$$h_{\max} = \lim_{H \longrightarrow \infty} \frac{H\left[\sqrt{(3l_{\text{inclined}}/H \tan\varphi) + (3 + (3C/\gamma H \tan\varphi))^2} - (3C/\gamma H \tan\varphi) + 3\right]^2 - 36H}{24}. \tag{30}$$

That is,

$$h_{\max} = \frac{l_{\text{inclined}}}{4 \tan \varphi}, \tag{31}$$

where l_{inclined} is the inclined span of loose layer arch, m; $\sum M$ is the bedrock layer thickness, m; α is overburden fracture angle, °; H is the thickness of the loose layer arch up to the overlying rock layer, m.

6. Classification of Bearing Structure of Mining-Induced Loose Layer

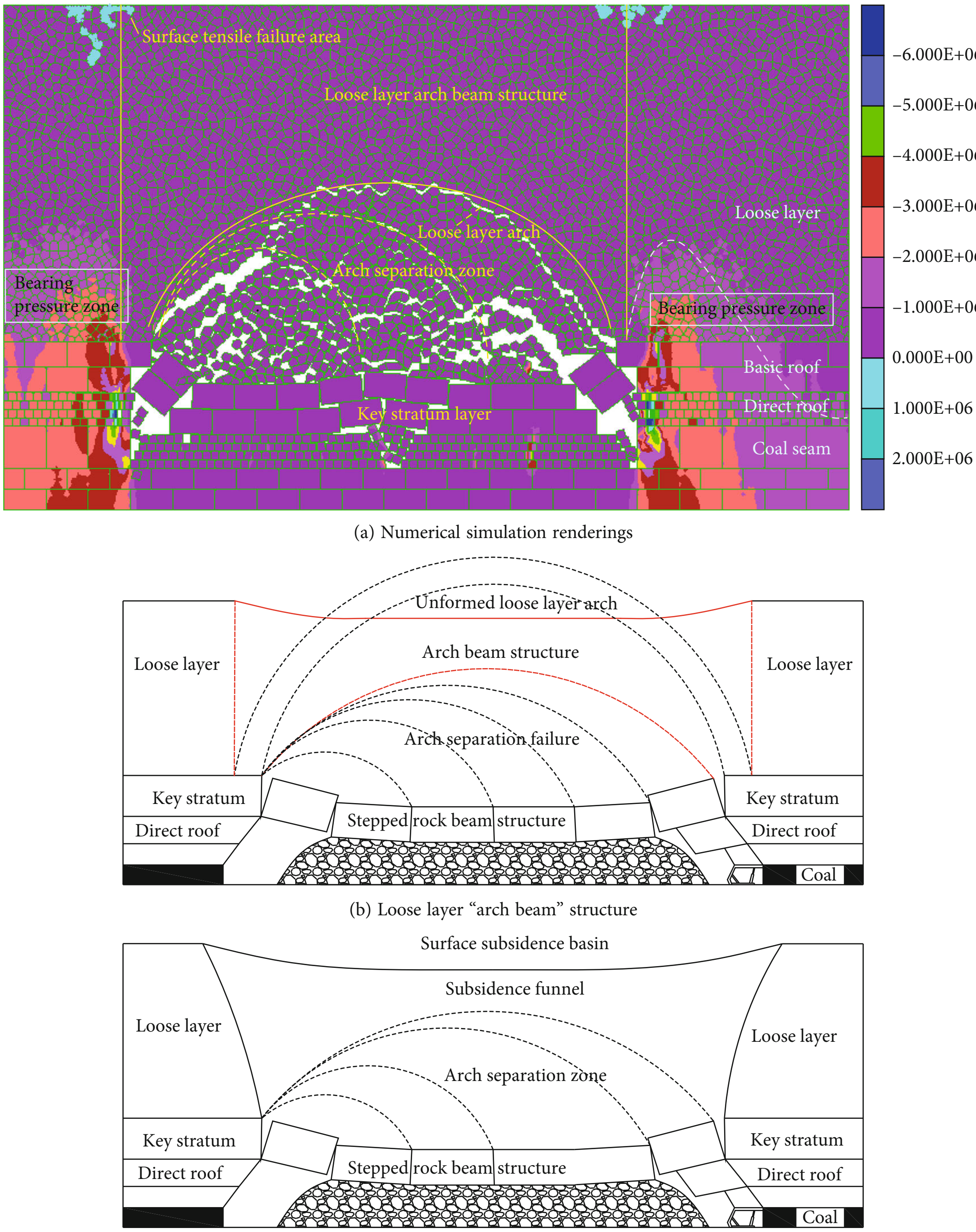
According to the thickness of loose layer, the bearing structure of mining-induced loose layer is classified as follows.

(1) Load type

When the loose layer is sandy loose layer, that is, cohesion $C = 0$, internal friction angle $\varphi = 0$, or when the loose layer is clayey loose layer, but when $\sum H < h_1 + (\delta_1/2)$, the loose layer arch bearing structure cannot be formed, and the loose layer acts as a load layer on the bedrock key layer.

(2) Arch beam destruction type

When $h_1 + (\delta_1/2) \leq \sum H < h_{max}$, the loose layer arch bearing structure is formed. With the advance of coalface, the arch develops upward, when $h + (\delta/2) \geq \sum H$, bearing

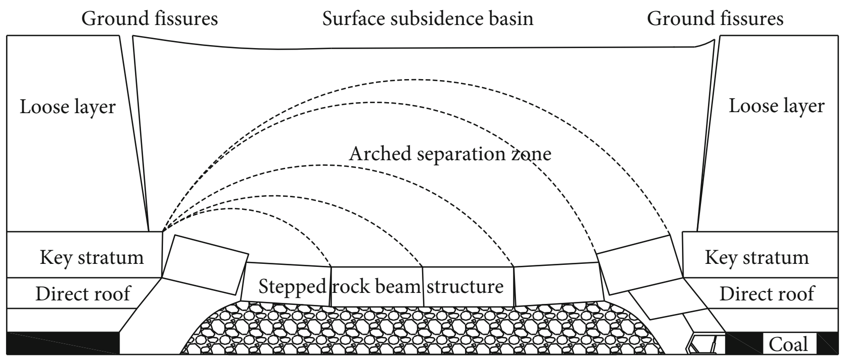


(a) Numerical simulation renderings

(b) Loose layer "arch beam" structure

(c) Unconsolidated strata settlement funnel

Figure 17: Continued.



(d) "Arch beam" failure and ground fissures

Figure 17: Arch beam structure and ground fissures.

Table 2: Determination of ground fissure generation.

Main key layer's collapse situation		Advancing distance of coalface/m	Loose layer arch structure			Determination of ground fracture generation	
			Span/m	Arch height/m	Arch thickness/m	σ_{max}/kPa	Judgment
First break		24	9.37	3.89	1.65	34.4	No
Cycle breakage	1	32.01	17.38	7.03	2.79	66.63	No
	2	40.02	25.39	9.98	3.73	102.0	Yes

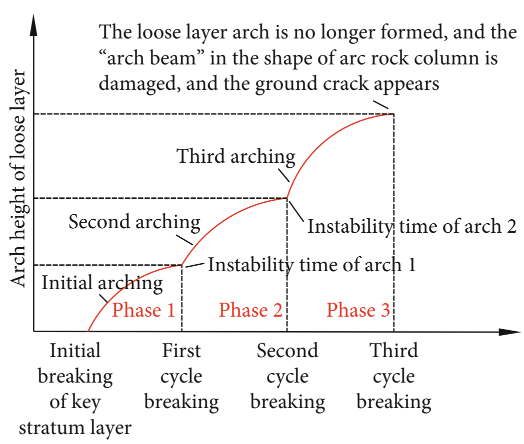


Figure 18: Stage development characteristics of arch structure.

structure arch is no longer formed. Moreover, when the loose layer develops to a certain height, the overlying loose layer will present the "arch-beam destruction" type with the upper part as "beam" and the lower part as "arch."

(3) Limit arch height type

When $\sum H > h_{max}$, the loose layer arch bearing structure formed and reached the maximum height h_{max} and then no longer developed upward, the loose layer structure was "tunnel" type forward extension.

7. Initial Ground Fissure Prediction Method

7.1. Structural Stability Analysis of "Arch Beam" with Thickly Sticky Loose Layer. With the advance of coalface and the upward development of loose layer arch structure, overlying loose layer will eventually present an "arch beam" structure with the upper part as a "beam" and the lower part as an "arch." Before the formation of ground fissures, the "arch beam" is in a self-stable state. The stress analysis of the right arch of the loose layer arch structure is shown in Figure 13, in which vault position is point B, arch foot is point C, ρ is sandy soil density, and g is acceleration of gravity. The equation of the catenary "arch" below is $f(x) = -H\text{ch}\sqrt{(\gamma/F_H)}x$, in which the distance between the vault and the ground surface is H.

The internal stress distribution in the beam [7] is

$$\begin{cases} \sigma_x = -\dfrac{\rho g x}{f'(x)} + \dfrac{\rho g x y}{f(x) f'(x)} + \dfrac{\rho g y}{f'^2(x)}, \\ \sigma_y = \rho g y, \\ \tau_{xy} = \dfrac{\rho g y}{f'(x)}. \end{cases} \tag{32}$$

The maximum normal stress in the beam σ_{max} is

$$\sigma_{max} = \left(\mu + \sqrt{\mu^2 + sxy(1-t)}\right)\rho g, \tag{33}$$

where $\mu = s^2 y - sx + sxt + y/2$, $s = 1/f'(x) = -1/H\sqrt{(\gamma/F_H)}$ sh$\sqrt{(\gamma/F_H)}x$, and$t = y/f(x) = -y/H\text{ch}\sqrt{(\gamma/F_H)}x$

Table 3: Prediction of ground fissures in typical working faces in Shendong mining area.

Name of coalface	Drill hole name	Loose layer thickness/m	Loose layer type	Initial fracture distance from stop line/m		
				Theoretical value	Measured value	Error
Halagou Mine 22207	Q29	40.6	Arch beam destruction type	25.39	26.5	4.19%
Shiyatai Mine 22306	K72	43.2	Arch beam destruction type	60.3	63	4.29%
Halagou Mine 22413	Q104	43.55	Arch beam destruction type	130.5	135	3.33%
Shangwangang Mine 12401	R102	13.95	Loaded type	90.1	94	4.15%
Daliuta Mine 52305	J178	22.45	Arch beam destruction type	129.7	134.2	3.35%

σ_{max} has a maximum value at the upper boundary $y = 0$, $\partial\sigma_{max}/\partial x = 0$, that is, when

$$x = \frac{l}{2\text{arcch}(H + h/H)}, \tag{34}$$

$$\sigma_{max} = \frac{\rho g l^2}{6.17H\text{arcch}^2(H + h/H)}. \tag{35}$$

Suppose the cohesive force of loose layer is $[\sigma]$, then,

(1) When $\sigma_{max} < [\sigma]$, there will be no cracks on the upper boundary of the "arch beam"

(2) When $\sigma_{max} \geq [\sigma]$, the initial ground fissures will appear on the upper boundary of the "arch beam." At this time, the limit span of arch beam is

$$l = \sqrt{\frac{6.17[\sigma]H\text{arcch}^2(H + h/H)}{\rho g}}. \tag{36}$$

The corresponding coalface advance distance L is

$$L = \sqrt{\frac{6.17[\sigma]H\text{arcch}^2(H + h/H)}{\rho g}} + 2\sum M \cdot \cot\alpha. \tag{37}$$

Because the leading crack angle is distributed in the form of approximate vertical angle, it can be considered that the surface crack appears above the coal wall of the coalface [32].

Therefore, the horizontal distance L_B between the initial ground fissures and the open-off cut of the coalface is

$$L_B = \sqrt{\frac{6.17[\sigma]H\text{arcch}^2(H + h/H)}{\rho g}} + \sum M \cdot \cot\alpha. \tag{38}$$

Occurrence time T of initial ground fissures is

$$T = \frac{\sqrt{\left(6.17[\sigma]H\text{arcch}^2(H + h/H)/\rho g\right)} + 2\sum M \cdot \cot\alpha}{N}, \tag{39}$$

where T is the time of initial tensile fissures, day; N is the average advance speed of coalface, m/day.

7.2. Prediction Method of Initial Ground Fissures. Based on the TSLLA structure model and the loose layer arch beam structure model, the initial ground fissures prediction method is proposed as shown in Figure 14. The detailed steps are as follows.

(1) According to the borehole histogram of the coalface and the physical and mechanical properties of rock and soil layer, the key layer is distinguished, the movement characteristics of the overburden structure of the bedrock layer are analyzed from bottom to top, and the corresponding relationship between the arch span of the loose layer, the breaking distance of the main key layer, and the advancing distance of the coalface is obtained

(2) The mining loose layer structure is classified according to the collapse step of the main key layer, the thickness of the loose layer, and the physical and mechanical properties

(i) If $\sum H < h_1 + (\delta_1/2)$, the loose layer bearing structure cannot be formed, the loose layer acts as a load layer on the bedrock key layer, when the bedrock key layer occurs the first break, the ground fissures will appear. The horizontal distance between the initial ground fissures and the open-off cut is $L_{Bi=} L_1$

(ii) If $\sum H > h_{\max}$, the loose layer structure is extended forward in the form of "tunnel," no fissures will appear on the surface

(iii) If $h_1 \leq \sum H \leq h_{\max}$, the loose layer arch structure is formed and finally present "arch beam destruction" type

(3) According to the dynamic evolution mechanism of the loose layer arch structure, the judgment analysis of the stability of the loose layer arch is carried out, and then the time and location of the initial ground fissures are predicted and calculated

When the main key stratum collapses for the ith time, i span l_i for loose layer arch structure is

$$l_i = \left(\frac{\tan\varphi}{3}\sqrt{\left(36\sum H - 12h_i\right)\left(\sum H - h_i\right)} + \frac{2C}{\gamma}\right) \times \left(\sqrt{\frac{36\sum H - 12h_i}{\sum H - h_i}} - 6\right), \tag{40}$$

where l_i is the arch span of the loose layer when the main key layer collapses at the ith time, m; h_i is the height of loose arch structure i, m.

(i) If $h_i + (\delta_i/2) > \sum H$, the arch of the loose layer is no longer formed, and the horizontal distance between the initial ground fissure and the open-off cut of the coalface L_{Bi} is

$$L_{Bi} = L_i. \tag{41}$$

(ii) If $h_i + (\delta_i/2) \leq \sum H$, and $l_i < \sqrt{6.17[\sigma]H_i \text{arcch}^2(H_i + h_i/H_i)/\rho g}$, that is, $[\sigma_{\max}]_i < [\sigma]$, then, the loose layer arch i remains stable. With the advancement of the coalface and the breaking of the main key layer, it will continue to develop upward, and the maximum development height is shown in formula (34).

(iii) If $h_i + (\delta_i/2) \leq \sum H$, and $l_i \geq \sqrt{6.17[\sigma]H_i \text{arcch}^2(H_i + h_i/H_i)/\rho g}$, that is, $[\sigma_{\max}]_i \geq [\sigma]$, then the arch of the loose layer no longer develops upward, the arch beam of the loose layer is broken, the initial ground cracks appear, and the horizontal distance between the fissures and the open-off cut of the coalface L_{Bi} is

$$L_{Bi} = L_i, \tag{42}$$

where L_i is the advance distance of coalface when the main key stratum collapses at the ith time, m; H_i is the thickness of the overlying rock and soil layer of the loose arch structure, m; δ_i is the thickness of loose arch structure i, m; $[\sigma_{\max}]_i$ is the maximum tensile stress at the upper boundary of loose layer arch structure i, MPa.

8. Results and Discussions

8.1. Theoretical Derivation of Dynamic Evolution Law of Loose Layer Arch Structure. The following is a theoretical analysis of the dynamic evolution process of the loose layer arch structure and the influence on the surface cracks from a mechanical perspective.

(1) First of all, based on the key layer theory to analyze the bedrock layer movement characteristics. It can be known that the main key layer of the 22207 coalface is 6# fine sandstone (10.3 m), from the Formulas (43) and (44), calculate the initial breaking distance l_1 and periodic breaking distance l_c of the main key layer as follows

$$l_1 = h'\sqrt{\frac{2R_T}{q'}} = 19.63\text{m}, \tag{43}$$

$$l_c = h'\sqrt{\frac{R_T}{3q'}} = 8.01\text{m}. \tag{44}$$

According to Formulas (26) and (28), the corresponding relationship between the arch span of the loose layer and the breaking distance of the main key layer is calculated as follows:

$$\begin{aligned} l_1 &= L_{k1} - 10.26 = L_1 - 14.63\text{m}, \\ l_n &= L_{kn}\text{-}10.26 = L_n\text{-}14.63\text{m}. \end{aligned} \tag{45}$$

(2) Loose layer structure type

From Formulas (25) and (30), the minimum height of the loose layer arch that can be formed under the mining geological conditions of the 22207 coalface is $h_1 = 9.15$m, and the maximum height is $h_{\max} = 162.2$m.

The thickness of the loose layer at the 22207 coalface is $\sum H = 40.6$. On these basis, it is known that $h_1 \leq \sum H \leq h_{\max}$.

Therefore, the mining loose layer belongs to "arch beam destruction type" in the 22207 coalface.

8.2. Numerical Simulation of Dynamic Evolution Law of Loose Layer Arch Structure. After the coal seam is mined, the working face moves forward from the open cut, which first causes the collapse of the direct roof, and then the basic roof (key layer) separates, breaks for the first time, the rock blocks bite, rotate, and touch the gangue. In the process of rock stratum movement, uneven displacement occurs between the particles of the loose layer to form an "arch shell" structure to bear the upper load, while the lower sandy soil layer separates and collapses, as shown in Figure 15.

With the advance of the working face, the basic roof (key layer) is pressed for the first cycle, the bedrock rock block rotates to form a "stepped rock beam" or "masonry beam" structure, the arch foot of the loose layer is unstable and broken to form an "arch" separation zone to fill the goaf, and the loose layer is arched upward again based on the fracture position of the key layer to form a new "arch shell" structure. The "key layer-loose layer arch" structure takes this "breaking balance" reciprocating cycle process until the failure height of overburden reaches the maximum, as shown in Figure 16.

With the continuous advance of the coalface, the loose layer arch continues to develop upward. When the thickness of the loose layer is less than the sum of the theoretical arch height and half arch thickness of the loose layer, i.e., $\sum h < (H + \delta/2)$, loose layer arch cannot be formed. However, the strength of the surface sandy soil layer is low, when the loose layer structure develops to a certain height, and the overlying loose layer presents an "arch beam" structure with "beam" in the upper part and "arch" in the lower part, as shown in Figures 17(a) and 17(b). After the arch beam is unstable and broken, the loose layer has a "funnel-shaped" settlement, as shown in Figure 17(c). Uneven subsidence and movement deformation of various points on the surface cause surface cracks outside the upper direction of the excavation boundary, as shown in Figure 17(d).

8.3. Prediction for Initial Ground Fissures. According to Formulas (25) and (26) and (27) and (34), the stability determination of loose layer arch structure and theoretical analysis of dynamic evolution process of 22207 coalface are carried out, and then, the occurrence time and location of initial ground fissures are predicted and calculated, as shown in Table 2.

From Table 2 and Figure 18, it can be seen that when the 22207caolface is advanced to 40.02 m, the second periodic breakage occurs in the main key layer. The loose layer arch structure presents "arch beam" type damage, and the first ground fissures appear. The ground fissure is 25.39 m away from the horizontal distance of the open-off cut in coalface. Through the investigation of the surface of 22207 coalface, it is found that the horizontal distance between a series of collapse fissures initially formed on the surface and the open-off cut of the coalface is about 26.5 m, which is consistent with the theoretical analysis.

In addition, several typical coalfaces are selected to further verify the accuracy of the initial ground fissures prediction method, as shown in Table 3. It can be seen that the errors of the initial ground fracture prediction methods proposed in this paper are less than 5%, which are in good agreement with the actual measured values in the field. It has certain guiding significance for loss reduction mining and ecological restoration under the conditions of thickly sticky loose layers in the western mining area.

9. Conclusions

(1) A shallow buried TSLLA bearing structure mechanical model is constructed, and the structural stability of the loose layer arch is analyzed. With the increase of span, the ultimate arch height of the loose layer arch in the limit state increases nonlinearly and gradually; the greater the thickness of the loose layer, the greater the ultimate arch height and the ultimate span of the loose layer arch

(2) The dynamic evolution mechanism of the bearing structure of the TSLLA is revealed. In the process of mining, the arch collapse damage of the loose layer shows the development of "arch" from bottom to top and finally forms the "arch-beam" with "beam" above and "arch" below. Furthermore, the formula for calculating the most extreme height of the loose layer arch bearing structure is derived

(3) According to the different thickness of the loose layer, the bearing structure of the loose layer can be divided into three types: (1) load type: the bearing structure is not formed, and the loose layer acts as a load on the bedrock layer; (2) arch beam destruction type: the loose layer formed a bearing structure, the "break-balance" reciprocating cycle upward evolution in the process of coal mining, and finally "Arch beam destruction" type; (3) ultimate arch height type: the arch structure is formed inside the loose layer, and the arch height no longer changes when it develops to the ultimate height

(4) The structural mechanics model of "arch beam" in thickly sticky loose layer is constructed, the mechanism of the influence of the loose layer arch bearing structure on the ground fissures is revealed, the prediction method and calculation steps for initial ground fissures are proposed, and the formulae for the location and time of the initial ground fissures are illustrated

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

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