

Article

Research on the Response Mechanism of Overlying Strata Failure and Ground Fissures Development Under High-Intensity Mining

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Abstract

Mining-induced ground fissures in the Ordos Basin pose critical threats to coal mine safety and ecological stability. This study integrated multi-source monitoring data (improves data acquisition efficiency by 60%) with theoretical models to elucidate the dynamic response mechanism between overlying strata failure and ground fissure development. The results demonstrate that: (1) Two rock beam structural models for initial and periodic fracturing of thick, hard rock strata are established, demonstrating that both failure modes are dominated by tensile–shear mechanisms. (2) Ground fissures exhibit distinct zonal characteristics, displaying a gradient pattern of “strong disturbance in the near field and weak response in the far field.” Quantitative data support this pattern: average fissure density is 36/hm², with a maximum of 45/hm² recorded in the immediate vicinity of the working face, declining steadily outward. (3) Overlying strata failure forms three distinct zones—caving zone (42 m), fissure zone (158 m), and longitudinal penetrating zone—reflecting the heterogeneous fracture characteristics of medium-hard rock strata under mining influence. (3) The proposed “virtual main arch—virtual auxiliary arch” equivalent support system theory elucidates the mechanistic differences between step fissures (attributed to local support system instability) and collapse fissures (driven by global support system instability) from a mechanical perspective. The developed chain response theory fills a critical theoretical gap and provides a novel method for predicting and preventing geological disasters in mining areas.

Keywords: high-intensity mining; overlying strata failure; ground fissure; formation mechanism; development law



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1. Introduction

As the world’s largest developing country, China has seen a steady decline in coal consumption amid its “dual carbon” strategy [1–3]. Nevertheless, coal remains an irreplaceable “stabilizer” in national energy security in the short term [4,5]. With the continuous expansion of mining scale and the widespread application of intelligent mining technologies, the geological environmental problems caused by coal resource exploitation have become increasingly prominent. Among these, ground fissures—typical mining-induced damage—have emerged as a major geological environmental issue in China’s

major coal-producing areas. Ground fissures are not a localized phenomenon unique to China; rather, they represent a significant environmental and engineering challenge in all major coal-producing regions globally. In the United States, longwall mining operations in the Appalachian Basin often induce ground fissures that interrupt groundwater flow and damage residential structures. In Australia, the high-intensity mining of thick coal seams in the Bowen Basin results in extensive surface subsidence and permanent topographical alterations. Similarly, European mining districts in Poland and Germany face persistent challenges related to ground stability and soil degradation caused by historical and active mining activities. These global challenges underscore the urgent necessity of understanding the mechanical response mechanisms of the rock strata-surface system [2,3,6–10]. Aggregated quantitative data from global literature highlight the pervasive scale of this issue (Table 1). While the United States and Europe exhibit affected surface areas ranging from 1% to 7%, the most severe impacts occur in high-intensity regions like the Ordos Basin in China, where affected areas reach 10~15% and fissure length surpasses 200 m/hm².

Table 1. Representative quantitative indicators of ground fissure prevalence across global coal basins.

Region	Coal Basin	Affected Area (% of Surface)	Fissure Density (Fissures/hm ²)	Fissure Length (m/hm ²)
China	Ordos/Shanxi	10~15%	10~40	150~250
Australia	Bowen/Hunter	2~8%	5~12	50~100
United States	Appalachian	1~5%	2~5	20~60
Europe	Upper Silesia	3~7%	4~10	40~90

These ground fissures, interconnected with the water-conducting fissure zone formed by overlying strata failure, constitute a complete seepage channel. This not only increases the risk of mine water inrush but also accelerates vegetation degradation, severely restricting regional sustainable development. Furthermore, the development of a multi-scale fissure network alters surface runoff pathways and enhances subsurface permeability, which triggers secondary disasters such as piping and landslides. Engineering observations reveal that ground fissure activity directly contributes to structural damage in infrastructure, including wall cracking, door/window deformation in buildings, and utility pole tilting. In some areas, the weak plasticity of the soil leads to localized landslides with maximum sliding distances of up to 10 m [11,12]. The formation of ground fissures is highly sensitive to the synergy between objective geological conditions and the choice of mining methodology. In regions such as the Ordos Basin, the combination of shallow burial depths (<200 m) and extra-thick coal seams (8~16 m) creates an environment where high-intensity mining triggers extensive rock strata failure. However, research indicates that ground fissure development is not an unavoidable consequence of mining. Instead, their occurrence can be strategically restricted or prevented through the adoption of damage-reduction technologies. Specifically, limited-thickness mining attenuates the intensity of rock strata fracturing by reducing the total mining height. Pillarless mining techniques, such as gob-side entry retaining, homogenize the stress distribution and avoid localized surface ruptures caused by stress concentrations above residual pillars. Most effectively, backfill mining provides immediate structural support to the goaf, which minimizes overlying strata subsidence and stems the formation of fissures at the source. Therefore, in-depth revelation of the dynamic response mechanism between overlying strata failure and ground fissure development is essential to provide the scientific parameters necessary for optimizing these mitigation strategies.

In recent years, scholars have made systematic advances in understanding the mechanisms. Regarding overlying strata failure mechanisms, the introduction of the key stratum

theory and voussoir beam theory provided a novel theoretical framework for elucidating rock strata movement. Studies have demonstrated that the key stratum plays a decisive role in governing overlying strata movement during mining. Upon fracturing, the voussoir beam structure formed by this key stratum continues to bear the primary load, offering a rational explanation for the development of dislocations within the overlying strata [13–18]. Furthermore, a stress shell structure has been identified in the surrounding rock of working faces, confirming its role as the primary load-bearing structure for overlying strata. The stability of the stress shell can now be used to control mine pressure, marking a significant advancement in practical mining engineering [19,20].

Research on the development laws of ground fissures has undergone a profound evolution from phenomenological observation to mechanistic elucidation. Leveraging extensive in situ monitoring data, scholars have summarized the spatial distribution patterns and established prediction models [21,22]. With advancements in computational technology, numerical simulation has emerged as a powerful tool for analyzing fissure development: by investigating stress distribution and plastic zone evolution, researchers have revealed that the surface rupture often initiates prior to goaf formation [23,24]. Physical modelling has provided critical insights into the development of penetrating fissures, proposing failure criteria and a method to predict fissure location, which helps quantify the mechanical thresholds for fissure propagation [25–27]. Furthermore, advanced mathematical methods—including principal component analysis (PCA), backpropagation (BP) neural networks, and deep learning—have been employed to identify key factors influencing fissure development, enabling quantitative assessment of fissure risk in mining areas [28,29].

Monitoring technology innovations has provided robust data support. Traditional monitoring methods such as leveling and total station surveying, despite their high precision, suffer from limitations including low efficiency and high labor intensity [30,31]. In recent years, InSAR technology has enabled millimeter-scale precision monitoring of large-area surface deformations. UAV photogrammetry offers centimeter-resolution capabilities for ground fissure identification, and 3D laser scanning technology achieves fine quantification of fissure morphological parameters [32–34]. In the field of underground monitoring, micro seismic monitoring technology effectively captures internal rock mass fracture signals, while distributed fiber optic sensing technology provides continuous monitoring data on rock mass strain distribution [35]. Currently, monitoring technology is rapidly evolving toward the direction of multi-source data fusion to achieve a more comprehensive characterization of mining damage.

Despite extensive research on rock strata movement and fissure distribution, a critical knowledge gap remains regarding the co-evolution mechanisms under high-intensity mining, which limits the development of effective disaster mitigation strategies. Therefore, this study establishes a targeted research objective: to bridge the knowledge gap by elucidating the mechanical co-evolutionary mechanism between thick, hard strata failure and ground fissure development under shallow-buried, high-intensity mining conditions. The Ordos Basin is a representative mechanical prototype. By establishing the “virtual main arch—virtual auxiliary arch” equivalent support system theory, the research elucidates the mechanical origins of diverse surface damage patterns, and translates site-specific observations into a generalized mechanical framework. This framework directly contributes to engineering decision-making by allowing for the quantitative assessment of fissure risk and the identification of a “gradient distribution” for disasters, such as defining safety exclusion zones based on the “strong disturbance in the near field” and prioritizing surface restoration in “weak response far-field” areas. Meanwhile, the characterization of fissure-induced seepage channels supports long-term environmental management and regional

sustainable development (resource management and soil erosion control). Ultimately, this work provides a rigorous scientific baseline for promoting high-quality, green development in the coal industry.

2. Materials and Methods

2.1. Overview of the Study Area

The study area is situated within the Junger Coalfield, located on the northeastern margin of the Ordos Basin, China. It spans from $110^{\circ}45'$ to $111^{\circ}15'$ E and $39^{\circ}30'$ to $39^{\circ}45'$ N, covering an area of approximately 3.5 km^2 . Three mineable coal seams are present at depth: the No. 3, No. 6-1, and No. 6 coal seams. Among these, the No. 3 coal seam has an average thickness of 2.64 m, the No. 6-1 coal seam has an average thickness of 3.91 m, and the No. 6 coal seam is the thickest at 14.82 m. Notably, the average spacing between the No. 6-1 and No. 6 coal seams is less than 0.8 m in some local areas, posing challenges for mining operations. To address these geological constraints and achieve resource integration, a fully mechanized top-coal caving mining method with layered extraction has been implemented for practical exploitation. The study area is characterized by a typical loess hilly and gully landscape, with a general topography that slopes from north to south. Surface elevations range from 1115 to 1265 m, resulting in a maximum relief of 150 m. The region experiences a temperate continental arid climate, with an annual average precipitation of 439.5 mm (ranging from 267 to 640.8 mm) and annual evaporation exceeding 1800 mm. The annual average temperature is 7.8°C , and the area is subjected to 35–60 days of strong winds per year.

The 615 working face, targeting the combined mining of the No. 6-1 and No. 6 coal seams, has a mining dimension of 300 m (length) $\times$ 110 m (width). With a maximum mining thickness of 16 m, the working face advances at a rate of 4 m/d and operates at an average mining depth of 200 m. Characterized as a nearly horizontal coal seam (dip angle $< 5^{\circ}$), it is overlain by Quaternary aeolian sand. High-density resistivity method exploration reveals distinct resistivity anomaly zones directly above the goaf area, indicating that overlying strata movement and deformation have triggered the vertical propagation of the fissure zone. Due to the weak plasticity of the aeolian sand and mining-induced impacts, extensive ground fissures have developed, leading to soil erosion, damage to surface structures, and even localized landslides (with a maximum sliding distance of 10 m), as shown in Figure 1.

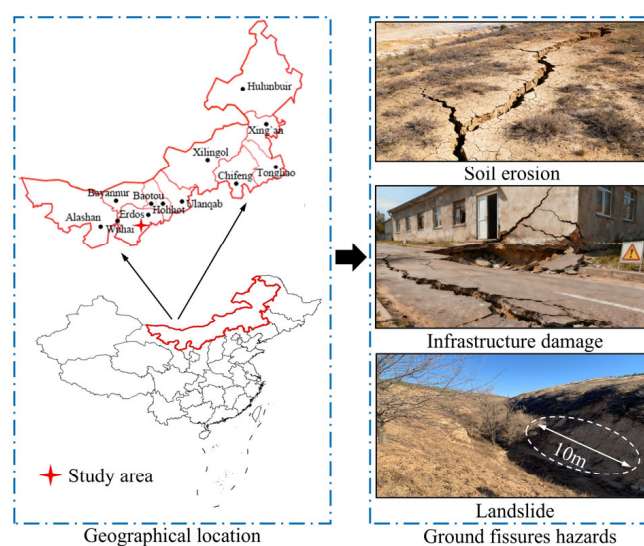


Figure 1. Geographical location of the study area.

2.2. Research Method

2.2.1. Monitoring Method

To address the challenges of numerous, widely distributed, and dynamically evolving ground fissures, this study establishes a “zonal-directional refined monitoring” multi-source data synergy system. The monitoring area is partitioned into three functional zones based on geological surveys and mining design plans. Boundary Tensile Zones: Located along the tailgate and open-off cut areas, these zones target tensile fissures. The monitoring focuses on long-term expansion behavior driven by concentrated tensile stress. Near-field Dislocation Zones: Situated immediately above the active mining area, these units monitor step fissures. The criteria involve tracking vertical displacements and rock strata dislocation trajectories. Goaf Stability Zones: These zones are designated for identifying collapse fissures and collapse pits. The monitoring corresponds to areas of high-stress enrichment or poor rock mass integrity where global support system instability is likely. High-resolution digital orthophoto maps (DOMs) of the study area are acquired using an unmanned aerial vehicle (UAV) equipped with an oblique photogrammetry system (resolution: ≤ 5 cm/pixel). Combined with an improved U-Net network, automatic fissure extraction and vectorization are performed to systematically analyze the spatial distribution characteristics of cracks—including position, orientation, connectivity, and development density. This systematic zoning allowed for a three-tier dynamic monitoring network, integrating macro-scale identification with centimeter-level tracking to capture the full-process coverage of fissure morphology:

Tier I: Total stations are used to establish a three-dimensional coordinate reference network for typical single fissures, providing a stable spatial framework for subsequent monitoring.

Tier II: Real-Time Kinematic (RTK) mobile stations are employed to conduct centimeter-level dynamic tracking of fissure endpoints, intersections, and other characteristic points, obtaining opening-closing degree time-series data during the mining cycle.

Tier III: Handheld laser rangefinders combined with tape measures are used for periodic verification of fissure width, length, and other morphological parameters, ensuring data accuracy.

Through multi-source heterogeneous data fusion inversion, a three-level collaborative monitoring system is formed: macro-deformation identification (DOM)—coordinate point tracking (RTK/total station)—morphological parameter quantification (tape measure). For the monitoring of the “two zones” (fracture zone and plastic zone) height in the overlying strata, borehole television and drilling fluid loss observation techniques are integrated to obtain the development height of the “two zones” and rock mass failure characteristics after mining. Additionally, borehole inclinometers are used to monitor the overall tilt deformation of the overlying strata. This technical system achieves full-process coverage of ground fissure morphology and overlying strata damage characteristics through an “air—space—ground—borehole” four-dimensional linked observation framework, providing multi-dimensional data support for revealing the control mechanism of overlying strata structural evolution on surface movement and deformation. The integrated framework enhances data acquisition efficiency by 60% relative to traditional single-source methods, and the identification accuracy of characteristic parameters is enhanced by several orders of magnitude (Figure 2).

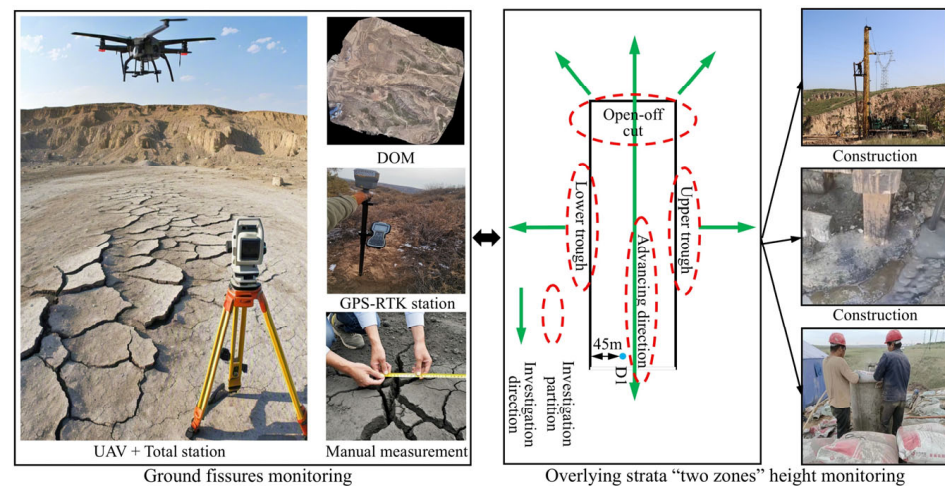


Figure 2. Monitoring methods.

2.2.2. Physical Model Experiment

Coal mining is a complex black-box problem, where the failure propagation process of the overlying strata cannot be directly measured in the field, necessitating complementary investigation via alternative methods. Similar material simulation experiments occupy a pivotal position in mining engineering research. The core principle of this method lies in constructing a physical model that adheres to similarity laws—maintaining geometric shape, kinematic behavior, and dynamic response proportionality with the physical prototype. By observing deformation, failure, and collapse processes within the model, researchers can extrapolate mechanical phenomena and rock strata movement patterns expected in actual engineering scenarios. A key advantage of this approach is its ability to intuitively, economically, and efficiently replicate internal stress changes and failure processes in rock masses that are difficult to observe directly in field conditions.

In practical mining applications, such experiments often utilize stratified rock mass models. Researchers employ optical photogrammetry systems to capture the movement trajectories and failure modes of the overlying strata during mining, providing critical experimental data to analyze the failure propagation process of the overlying strata. This experiment, conducted using the self-developed similar simulation system of the research group, aims to reveal the overlying strata damage and surface movement patterns induced by shallow-buried extra-thick coal seam mining through physical modeling. The model design is based on the actual geological and mining conditions of the mining area. The physical model experiment utilizes stratified rock mass models designed to adhere to similarity laws, ensuring that geometric shape, kinematic behavior, and dynamic response are proportional to the prototype. The geometric similarity ratio (α_L) is determined based on the boundary angle of rock strata movement and the dimensions of the physical experimental platform. With a prototype mining depth of 200 m and a model frame height of 0.5 m, the ratio is established as $\alpha_L = 1:400$. Based on the measured bulk density of the prototype rock mass and the calculated usage of sand, gypsum, and lime in the model, the bulk density ratio (α_γ) is determined to be $\alpha_\gamma = 1:1.5$. Following the principles of mechanical similarity, the stress ratio (α_σ) is derived as the product of the geometric and bulk density ratios ($\alpha_\sigma = \alpha_L \times \alpha_\gamma$). Substituting the aforementioned values yields $\alpha_\sigma = 1/400 \times 1/1.5 = 1/600$. To maintain kinematic similarity during the dynamic advancement of the working face, the time ratio (α_t) is calculated as $\alpha_t = \sqrt{\alpha_L}$. This resulted in $\alpha_t = \sqrt{1/400} = 1/20$, ensuring that the model can truly reflect the physical and mechanical behavior of the prototype. The material proportion and usage of the experimental model are shown in Figure 3.

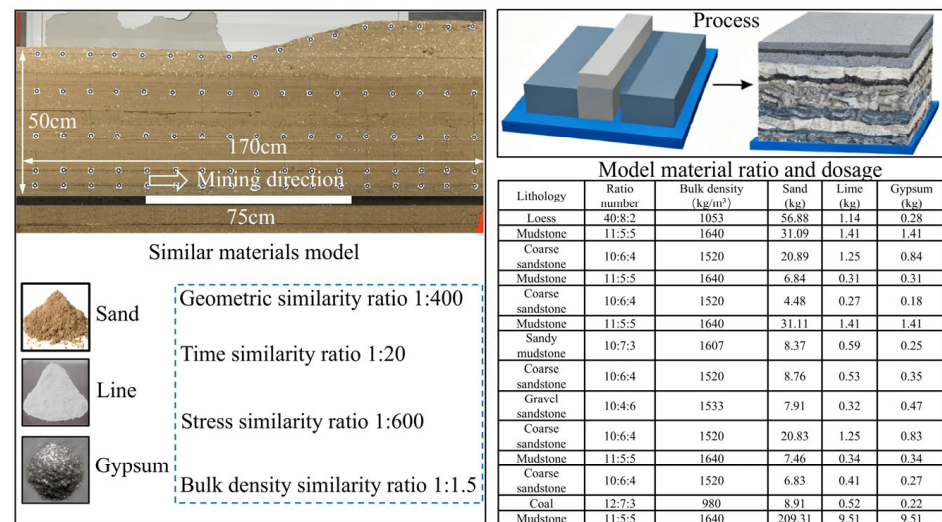


Figure 3. Similar materials model.

2.3. Analysis of Rock Strata Failure Instability Characteristics

During the working face mining process, the overlying strata undergo sequential initial and periodic fracturing. Existing studies have simplified thick, hard rock formations into shallow beam structures to analyze failure instability characteristics, where the span-thickness ratio significantly exceeds 5:1. However, under shallow-buried thick coal seam conditions prevalent in western mining areas, this simplification becomes fundamentally flawed as the rock strata thickness demonstrates substantial dimensional characteristics relative to span dimensions. Furthermore, the fracture mechanics and displacement patterns of rock strata directly govern the propagation mechanisms of overlying strata fissures, ultimately determining the development characteristics of ground fissures. To address these limitations, this study proposes a deep beam structural model for thick, hard rock strata. Through material mechanics analysis, we investigate the internal stress distribution characteristics of deep beam structures and systematically characterize their fracture patterns under varying span-thickness ratios.

To ensure the rigor of the mechanical analysis, the deep beam models for initial and periodic fracturing are based on the following key assumptions:

Homogeneity: The thick, hard rock strata are treated as homogeneous, isotropic, elastic deep beams.

Load Simplification: The self-weight of the thick, hard strata is neglected as an internal body force due to its relatively small thickness compared to the total overburden. Instead, it is converted into a uniformly distributed load q acting on the upper surface of the beam.

Dimensionality: The model accounts for the low span-thickness ratio prevalent in shallow-buried conditions, where the rock thickness h demonstrates significant dimensional characteristics relative to the span l .

For the clamped deep beam model representing initial fracturing, the undetermined coefficients in the stress function (Equation (2)) are determined by the following boundary conditions. At the upper surface ($y = -\frac{h}{2}$), the vertical stress $\sigma_y = -q$ and shear stress $\tau_{xy} = 0$. At the lower surface ($y = \frac{h}{2}$), the vertical stress $\sigma_y = 0$ and shear stress $\tau_{xy} = 0$. The ends of the beam ($x = 0$ and $x = l$) are subjected to zero rotation and displacement, satisfying the fixed-clamped constraint

For the cantilever deep beam model representing periodic fracturing, the coefficients in Equation (6) are resolved using these boundary conditions. The upper and lower boundary conditions for σ_y and τ_{xy} remain identical to the clamped model. The fixed end ($x = l$) maintains zero displacement, while the free end ($x = 0$) is subjected to zero horizontal

and shear stress. These constraints allow for the derivation of the 5th-degree polynomial stress functions, providing a precise characterization of the horizontal and shear stress concentration patterns that drive tensile–shear failure.

(1) Initial fracturing of thick, hard rock strata

During working face mining, the rock strata on both sides in a suspended state are clamped (fixed at both ends). Initial fracturing occurs when the suspended span attains the critical ultimate threshold. Therefore, a clamped deep beam structural model for the initial fracturing of thick, hard rock strata is established (Figure 4), where l is the length of the rock beam, h is the thickness, and q is the uniformly distributed load acting on the beam. It is important to note that as the beam thickness increases, its self-weight also rises. When the thickness reaches a critical value, the self-weight begins to influence the internal stress distribution of the beam. However, given the challenges in solving the self-gravity analysis of deep beam structures and the fact that the thickness of thick, hard rock strata is relatively small compared to the overlying strata, the self-weight of the thick, hard rock strata can be neglected. Instead, it is converted into a uniformly distributed load applied to the upper part of the rock beam.

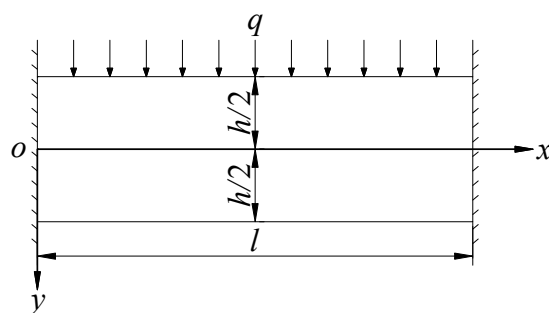


Figure 4. The clamped deep beam structure model when the thick, hard rock strata is broken for the first time.

The stress distribution within the rock beam is analyzed using the semi-inverse method. The stress function satisfies a 5th-degree polynomial to account for the complex boundary conditions of deep beam structures [36,37]:

$$\Phi = Ax^2 + Bxy + Cx^2y + Dy^2 + Ey^3 + Fxy^3 + G\left(\frac{y^5}{5} - x^2y^3\right) \quad (1)$$

where Φ is the stress function; x and y are the spatial coordinates; A, B, C, D, E, F, G are undetermined coefficients that are resolved based on the specific mechanical constraints of the beam.

In the absence of self-weight, the plane stress components can be expressed as:

$$\begin{cases} \sigma_x = \frac{\partial^2 \Phi}{\partial y^2} = 6Ey + 6Fxy + 2G(2y^3 - 3x^2y) + 2D \\ \sigma_y = \frac{\partial^2 \Phi}{\partial x^2} = 2Cy - 2Gy^3 + 2A \\ \tau_{xy} = \frac{\partial^2 \Phi}{\partial x \partial y} = -2Cx - 3Fy^2 + 6Gxy^2 - B \end{cases} \quad (2)$$

where $\sigma_x, \sigma_y, \tau_{xy}$ are the horizontal, vertical, shear stress of any point in the rock beam, respectively, Mpa.

According to the boundary conditions, the undetermined coefficients in Equation (2) can be determined [22,36,37]:

$$\begin{cases} y = -\frac{h}{2}, & \sigma_y = -q, & \tau_{xy} = 0 \\ y = \frac{h}{2}, & \sigma_y = 0, & \tau_{xy} = 0 \\ \sigma_x = -\frac{q(l^2+h^2-\mu h^2)}{h^3}y + \frac{6ql}{h^3}xy - \frac{6q}{h^3}x^2y + \frac{4q}{h^3}y^3 - \frac{\mu q}{2} \\ \sigma_y = \frac{3q}{2h}y - \frac{2q}{h^3}y^3 - \frac{q}{2} \\ \tau_{xy} = -\frac{3q}{2h}x - \frac{3ql}{h^3}y^2 + \frac{6q}{h^3}xy^2 + \frac{3ql}{4h} \end{cases} \quad (3)$$

where μ is the Poisson ratio.

The computational modeling and stress field visualization are conducted using MATLAB R2022b (MathWorks, Inc., Natick, MA, USA). To ensure reproducibility, the specific algorithms and functional parameters are detailed as follows:

- (1) Computational Environment: The Symbolic Math Toolbox is employed to solve the undetermined coefficients ($A \sim I$) in the 5th-degree polynomial stress functions defined in Equations (2) and (6).
- (2) Numerical Implementation: We utilize the solve function to satisfy the boundary conditions at the upper, lower, and lateral edges of the deep beam. For spatial visualization, the mesh-grid function establishes a coordinate system with a resolution of $0.1 \text{ m} \times 0.1 \text{ m}$, and the contour function generates the filled contour plots of the internal stress components.
- (3) Input Parameters: The simulation uses a Poisson's ratio (μ) of 0.3 and a uniformly distributed load (q) of 2.0 MPa. The geometric dimensions are set to a beam thickness (h) of 10 m and spans (l) ranging from 5 to 20 m, representing the varying span-thickness ratios observed in the Ordos Basin. These specific parameters ensure that the horizontal tensile stress at the midspan and the maximum shear stress at the supports are accurately quantified, facilitating the derivation of the ultimate spans l_t and l_s .

The results demonstrate that the horizontal stress, vertical stress, and shear stress within the rock beam exhibit symmetrical patterns with respect to the x-axis midline (Figure 5). As the working face advances further, the span-thickness ratio increases, leading to progressive amplification of horizontal stress and shear stress values, whereas the vertical stress remains constant. This phenomenon arises because horizontal stress and shear stress scale linearly with the beam span, while vertical stress depends solely on the applied load magnitude and beam thickness. Under the loading influence of overlying strata, the maximum horizontal stress concentrates at both lateral edges and the midspan of the rock beam. Notably, the lateral horizontal stress values first decrease and then increase from the top to the bottom of the rock beam. The shear stress reaches its peak values near the rock beam edges.

Combining Equation (3) and Figure 5, it is evident that at the midspan ($x = l/2$, $y = h/2$) of the clamped deep beam, the shear stress is zero, and the horizontal tensile stress at this position constitutes the maximum principal stress, which can be expressed as $\sigma_{x|\max} = \frac{ql^2}{4h^2}$. When $x = l$ and $y = 0$ or $x = 0$ and $y = 0$, the maximum shear stress is at (0, 0) or (l, 0) on both sides of the rock beam, which can be expressed as $|\tau_{xy}|\max = \frac{3ql}{4h}$. When the maximum principal stress at the midspan ($l/2, h/2$) reaches the rock's uniaxial tensile strength, tensile failure initiates at this location. Conversely, when the maximum shear stress at the supports ((0, 0) or (l, 0)) exceeds the rock's shear strength, shear failure occurs at the supports. According to the maximum tensile stress theory and maximum shear stress theory, the ultimate spans corresponding to tensile and shear failure can

be derived as Equations (4) and (5), respectively. It is observed that the ultimate span is proportional to the beam thickness and the material strengths, and inversely proportional to the applied load.

$$l_t = 2h\sqrt{\frac{R_t}{\eta q}} \quad (4)$$

$$l_s = h\frac{4R_s}{3\eta q} \quad (5)$$

where l_t , l_s are the ultimate span of the rock beam under tensile and tensile–shear failure, respectively; η is the rock strata failure coefficient; R_t , R_s are the tensile and shear strength, respectively.

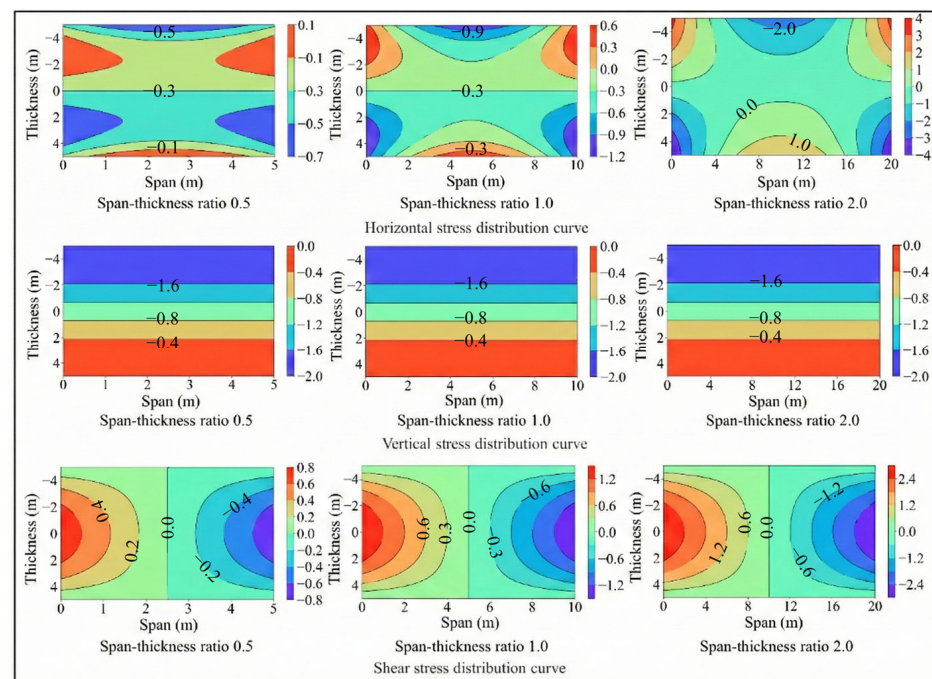


Figure 5. Internal stress distribution curve of clamped rock beam before the first breaking.

Under shallow-buried extra-thick coal seam conditions, the overlying strata are predominantly composed of sandstone–mudstone mixtures, with a tensile strength approximately 1/5 to 1/2 that of the shear strength and a rock strata failure coefficient ranging from 1.0 to 2.0. Consequently, under identical conditions, the ultimate span of a fixed-end deep beam at tensile failure is smaller than that at shear failure. This indicates that the initial fracturing mode of the rock strata is tensile–shear failure, with failure initiating at the lower boundary of the rock beam on both sides and in the middle.

(2) Periodic fracturing of thick, hard rock strata

After the initial fracturing of thick, hard rock strata, periodic fracturing occurs as the working face continues to advance. According to experimental simulation results, the thick, hard rock strata exhibit a fixed-end support state on one side and a cantilever state on the other side prior to periodic fracturing. Therefore, a cantilever beam model for the thick, hard rock stratum before periodic fracturing can be established, as shown in Figure 6. Where l_1 is the length of the rock beam, h is the thickness of the rock beam, and q is the uniformly distributed load acting on the rock beam.

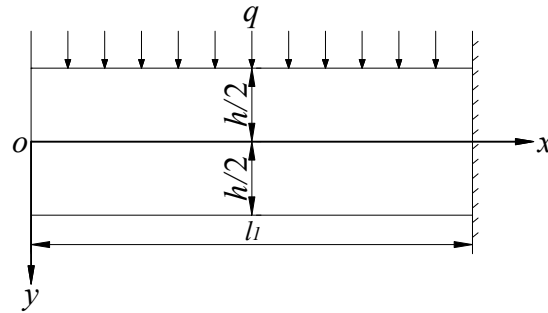


Figure 6. The cantilever deep beam structure model during periodic breaking of thick, hard rock strata.

According to the semi-inverse method, the real stress function of the cantilever deep beam structure satisfies a polynomial with the highest term of 5th degree [36,37]:

$$\Phi = 30x(E_1y + F_1y^2 + G_1y^3) + 15x^2(A_1 + B_1y + C_1y^2 + D_1y^3) + 30Hy^2 + 30Iy^3 - 5C_1y^4 - 3D_1y^5 \quad (6)$$

where $A_1, B_1, C_1, D_1, E_1, F_1, G_1, H, I$ are undetermined coefficients.

Reference Equation (2), the plane stress components can be expressed as:

$$\begin{cases} \sigma_x = \frac{\partial^2 \Phi}{\partial y^2} = (6G_1y + 2F_1)x + (3D_1y + C_1)x^2 + 6Iy - 2C_1y^2 - 2D_1y^3 + 2H \\ \sigma_y = \frac{\partial^2 \Phi}{\partial x^2} = B_1y + C_1y^2 + D_1y^3 + A_1 \\ \tau_{xy} = \frac{\partial^2 \Phi}{\partial x \partial y} = -(3D_1y^2 + 2C_1y + B_1)x - 2F_1y - 3G_1y^2 - E_1 \end{cases} \quad (7)$$

According to the boundary conditions, the undetermined coefficients in Equation (6) can be determined [22,36,37]:

$$\begin{cases} y = -\frac{h}{2}, & \sigma_y = -q, & \tau_{xy} = 0 \\ y = \frac{h}{2}, & \sigma_y = 0, & \tau_{xy} = 0 \\ \int_{-\frac{h}{2}}^{\frac{h}{2}} (\sigma_x)_{x=0} dy = 0, & \int_{-\frac{h}{2}}^{\frac{h}{2}} y(\sigma_x)_{x=0} dy = 0 \\ \sigma_x = -\frac{3q}{5h}y - \frac{6q}{h^3}x^2y + \frac{4q}{h^3}y^3 \\ \sigma_y = \frac{3q}{2h}y - \frac{2q}{h^3}y^3 - \frac{q}{2} \\ \tau_{xy} = -\frac{3q}{2h}x + \frac{6q}{h^3}xy^2 \end{cases} \quad (8)$$

It can be seen that both horizontal and shear stresses within the rock beam are symmetric about the y-axis midline (Figure 7). As the working face advances, the span-thickness ratio increases, leading to a gradual augmentation of both horizontal and shear stress magnitudes. Under the overlying strata load, maximum horizontal stress concentrates at the fixed end of the rock beam, where values first decrease and then increase from the top to the bottom. The maximum shear stress is also concentrated at the fixed end.

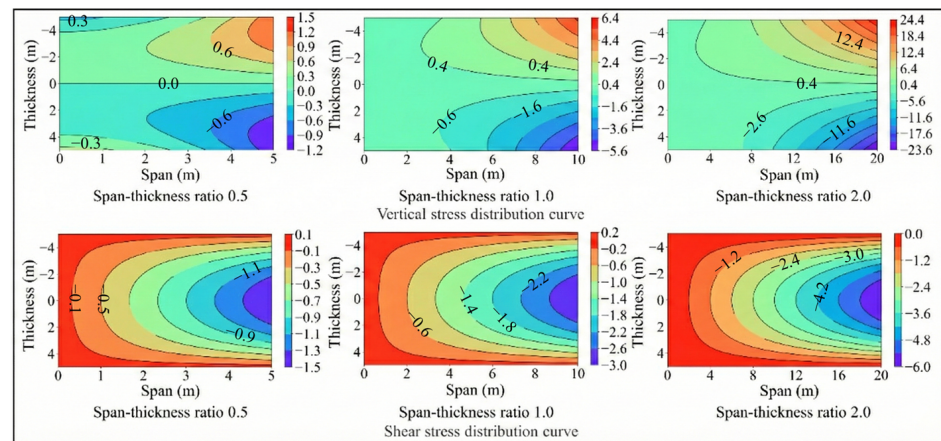


Figure 7. Internal stress distribution curve of cantilever deep beam before period breaking.

Combining Equation (8) and Figure 7, it can be seen that at the fixed-end upper top of the cantilever deep beam (where $x = l$, $y = -h/2$), the shear stress is zero, and the horizontal tensile stress at this position corresponds to the maximum principal stress, expressed as $\sigma_{x|_{\max}} = \frac{3ql^2}{h^2} - \frac{q}{5}$. When $y = 0$ (i.e., the fixed-end middle of the cantilever deep beam at $(l, 0)$), the location of maximum shear stress is identified, which can be expressed as $|\tau_{xy}|_{\max} = \frac{3ql}{2h}$. Therefore, the ultimate span corresponding to tensile and shear failure of the cantilever deep beam can be derived as Equations (9) and (10). It can be seen that the ultimate span is directly proportional to the thickness of the rock beam, tensile strength, and shear strength, and inversely proportional to the uniformly distributed load. Therefore, under identical conditions, the ultimate span of the cantilever deep beam at tensile failure is smaller than that at shear failure, indicating that the failure mode of the rock strata during periodic fracturing is tensile–shear failure, with the fracturing position occurring at the top (fixed-end upper surface) and middle (fixed-end middle) of the cantilever deep beam.

$$l_t = h \sqrt{\frac{R_t}{3\eta q} + \frac{1}{15}} \quad (9)$$

$$l_s = h \frac{2R_s}{3\eta q} \quad (10)$$

2.4. Mechanical Interpretation of Fissure Propagation

During the advance of the working face, the overlying strata undergo initial and periodic fracturing, manifested as initial fracturing traces on the side of the open-off cut and periodic fracturing traces on the advancing side. The shape and position of these fracturing traces are closely linked to the stress characteristics of the rock strata structure [22]. The Griffith criterion posits that rock failure arises from the initiation and propagation of fissures: when the tensile stress at a fissure tip exceeds the material's tensile strength limit, fracture occurs. A key tenet of the criterion is that the sum of the two principal stresses in the material must be greater than zero for tensile failure to initiate. Additionally, under predominantly compressive stress conditions, fissures close under compression, generating friction between their surfaces, which inhibits further propagation. Figure 8 illustrates the propagation law of internal fissures in rock under varying principal stress orientations: when the principal stress is perpendicular to, parallel to, or oblique to the fissure extension direction, stress concentration occurs at the fissure tip or end, driving subsequent expansion [22,36].

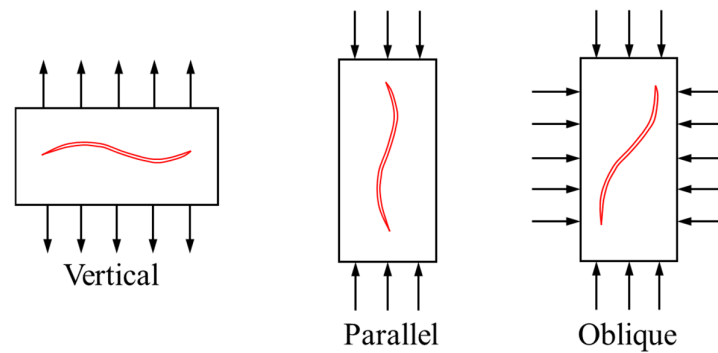


Figure 8. Fissure propagation law under different principal stress directions.

The theoretical analysis results of Section 2.3 show that the initial and periodic fracturing of rock strata occur at the end of the rock beam, and under the action of the maximum shear stress and the maximum principal tensile stress, the fissure will expand at a certain angle, as shown in Figure 9. A fan-shaped region with a radius r and a central angle φ can be formed by extending the bottom of the fissure at a point with the advantage of the rock, and there is $\tan \beta_1 < \tan \beta_0 < \tan \beta_2$ [22,36].

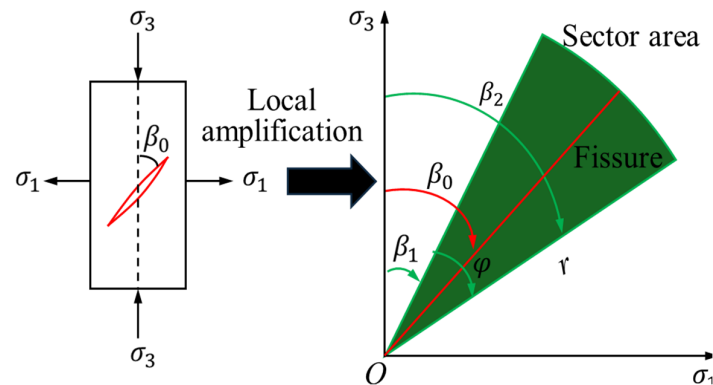


Figure 9. Fissure stress state.

According to the fissure propagation criterion, the angle domain satisfies Equations (11)–(13):

$$\tan \beta_1 = \frac{(\sigma_1 + \sigma_3) - \sqrt{(\sigma_1 + \sigma_3)^2 + 4(f\sigma_3 + \chi\sigma_t)(f\sigma_1 - \chi\sigma_t)}}{2(f\sigma_3 + \chi\sigma_t)} \quad (11)$$

$$\tan \beta_2 = \frac{(\sigma_1 + \sigma_3) + \sqrt{(\sigma_1 + \sigma_3)^2 + 4(f\sigma_3 + \chi\sigma_t)(f\sigma_1 - \chi\sigma_t)}}{2(f\sigma_3 + \chi\sigma_t)} \quad (12)$$

$$\begin{aligned} \tan \varphi = \tan(\beta_2 - \beta_1) &= \frac{\tan \beta_2 - \tan \beta_1}{1 + \tan \beta_2 \tan \beta_1} \\ &= \frac{\sqrt{(\sigma_1 + \sigma_3)^2 + 4(f\sigma_3 + \chi\sigma_t)(f\sigma_1 - \chi\sigma_t)}}{f(\sigma_3 - \sigma_1) + 2\chi} \end{aligned} \quad (13)$$

where σ_1 is the maximum principal stress, MPa; σ_3 is the minimum principal stress, MPa; f is the friction coefficient; χ is the fracture criterion coefficient; σ_t is the tensile strength, MPa. Assuming that the central angle φ of the fissure in the rock is small and the expansion direction is approximately extended along β_0 expansion, according to the geometric relationship, it can be obtained:

$$\tan 2\beta_0 = \tan(\beta_1 + \beta_2) = \frac{\tan \beta_2 + \tan \beta_1}{1 - \tan \beta_2 \tan \beta_1} = \frac{1}{f} \quad (14)$$

$$\beta_0 = \frac{1}{2} \arctan \frac{1}{f} \quad (15)$$

Equations (14) and (15) reveal an inverse correlation between fissure orientation angle and friction coefficient: for a given friction coefficient, the fissure orientation angle remains constant, implying that the fissure propagation direction within a homogeneous rock strata is essentially invariant. The orientation and propagation of fissures within the rock mass are fundamentally governed by the friction coefficient (f). Table 2 presents the quantitative relationship between the friction coefficient and the theoretical orientation angle (β_0) for various rock types under differing moisture conditions.

Table 2. Friction coefficients and orientation angles of different rocks.

Rock Type	Friction Coefficient (f , Dimensionless)		Orientation Angle (β_0 , °)	
	Dry	Moist	Dry	Moist
Granite	0.47~0.55	0.46~0.53	30.6~32.4	31.0~32.6
Quartzite	0.46~0.48	0.48~0.50	32.2~32.6	31.7~32.2
Hard sandstone	0.43~0.48	0.43~0.45	32.2~33.4	32.9~33.4
Soft sandstone	0.22~0.42	0.20~0.40	33.6~38.8	34.1~39.3
Mudstone	0.20~0.25	0.15~0.20	38.0~39.3	39.3~40.7

The orientation angle β_0 is calculated based on the Griffith failure criterion, where $\tan 2\beta_0 = \frac{1}{f}$. As shown in the table, harder rock types like granite exhibit higher friction coefficients and smaller orientation angles, whereas softer rocks like mudstone display the opposite trend. This inverse correlation confirms that the lithological combination of the overlying strata maintains a relatively stable fracturing trajectory. Since the overlying strata are predominantly composed of mudstone and sandstone (a combination of soft and hard lithologies), the variation in fissure propagation direction between these strata is minimal. This results in fissure traces on both sides of the overlying strata approximating a straight line, which is consistent with the findings of experimental simulations.

3. Results and Analysis

3.1. Development Characteristics of Ground Fissures

Figure 10 illustrates the distribution characteristics of ground fissures under high-intensity mining conditions. Based on formation mechanisms, ground fissures are categorized into three types: tensile fissures, step fissures, and collapse fissures. Tensile fissures manifest as narrow, elongated features (corresponding to Figure 10(②)) with orientations perpendicular to the mining direction, reflecting brittle failure of the shallow weathered layer induced by concentrated tensile stress. Step fissures, formed by differential sliding of rock strata, present as stepped displacements (corresponding to Figure 10(④)) with a maximum step height of 680 mm. These fissures distribute along the coal seam strike and are dominated by shear sliding, representing a progressive deformation mode. Collapse fissures occur suddenly (Figure 10(⑤)), characterized by widths exceeding 200 mm (up to 1170 mm in maximum) and penetration through the bedrock. Accompanied by 3~10 m deep collapse pits in the vicinity, their formation is associated with the “two-zone” mode of rock strata movement. The fissure network acts as a water-conducting channel, further exacerbating piping disasters. The maximum distances from the outermost ground fissures in the tailgate area and the open-off cut area to the working face boundary are 36 m and 38 m, respectively. Calculations reveal that the dip angle of the upper slope fissure (83.7°) is greater than that of the strike fissure (80.9°), which in turn exceeds the dip angle of the lower slope fissure (79.8°). These results conform to the Coulomb-Mohr failure criterion,

indicating that the rotation of the maximum principal stress direction (from vertical to horizontal) is the primary controlling factor for the directional propagation of fissures.

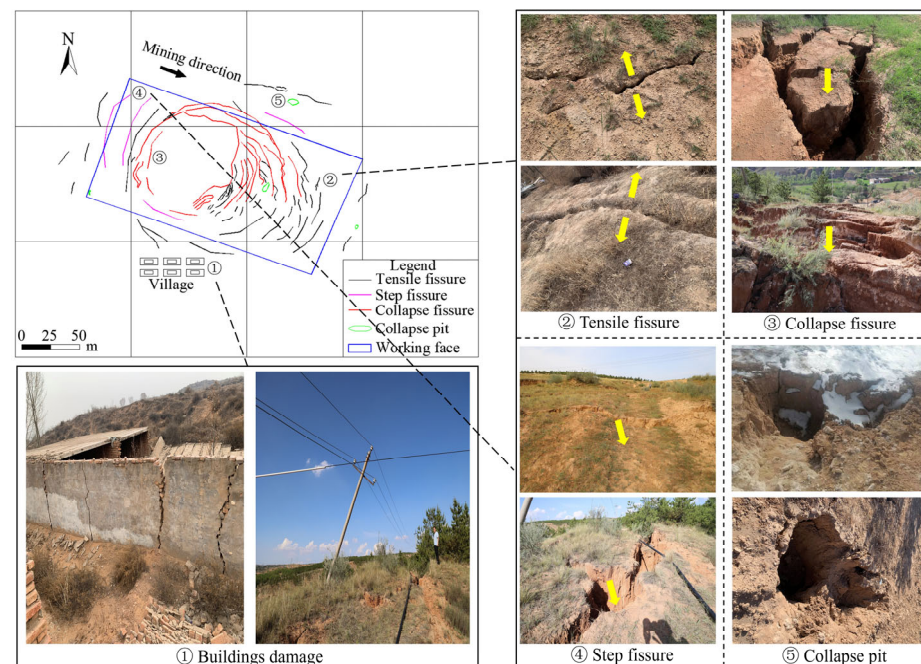


Figure 10. Types of ground fissures.

The distribution of ground fissures is strongly influenced by mining direction and working face dimensions, with tensile fissures predominantly concentrated within stress concentration zones. Step fissures (a key classification aligned with mining-induced fracturing mechanisms) exhibit regular, spatially correlated patterns that mirror rock strata displacement trajectories. Collapse fissures, often co-occurring with extensive collapse pits, are spatially clustered in high-stress enrichment zones or areas of poor rock mass integrity. Collectively, these fissure types form a contiguous network that extends from the immediate mining area to adjacent villages, where structural damage to buildings—such as wall cracking, door/window deformation, and utility pole tilting—has been directly attributed to ground fissure activity (corresponding to Figure 10(①)). In terms of damage progression, building structures undergo a clear three-stage deterioration: early-stage development of fissures with widths < 10 mm; middle-stage expansion to 50~100 mm wide fissures that induce door/window deformation; and late-stage escalation to utility pole tilting and slope sliding. This multi-scale, multi-type fissure network not only alters surface runoff pathways but also enhances subsurface permeability, thereby triggering secondary disasters (e.g., water infiltration, soil erosion). The intensity of fissure development shows a positive correlation with the depth-thickness ratio of the overlying strata, reflecting the combined effects of strata mechanics and mining-induced stress redistribution.

A notable gradient characterizes the fissure disaster zone: subtle ground fissures and building wall cracking transition abruptly to large-scale rock-soil mass collapses—evident in tensile fissures, structural damage, and collapse pits. This gradient, coupled with topographic abruptness (indicated by step fissures) and the large depth-width ratios of collapse fissures, demonstrates the multifaceted impact of high-intensity mining on surface morphology and structures. The effects range from progressive, cumulative damage (e.g., gradual fissure widening) to sudden, catastrophic events (e.g., slope failures). Furthermore, fissure development density and damage intensity exhibit a distinct spatial pattern: they increase sharply with proximity to the working face, reaching a peak in the “near field”

(adjacent to the working face), and decrease rapidly with distance, forming a “strong disturbance in the near field and weak response in the far field” gradient. Quantitative data support this pattern: average fissure density is $36/\text{hm}^2$, with a maximum of $45/\text{hm}^2$ recorded in the immediate vicinity of the working face, declining steadily outward.

Figure 11 illustrates the variation in width and depth of two primary fissure types—boundary fissures (located at the edge of the working face) and in-face fissures (within the working face). For boundary fissures, width remains relatively stable (0.18 m) during the initial stage of advancement (0–120 m). As the working face advances beyond 120 m, fissure width increases rapidly, stabilizing at 1.32 m once the face has advanced 240 m. Fissure depth exhibits a congruent trend, originating at 33 cm and advancing steadily to a stable value of 78 cm as the working face progresses. This variation is attributed to the persistent location of boundary fissures within the surface tensile zone, where tensile stress—induced by mining-induced strata movement—drives rapid expansion of fissure width and depth in the early-to-mid stages of advancement. In the later stages, as the strata reach a new equilibrium state, the rate of fissure growth slows, and both width and depth stabilize.

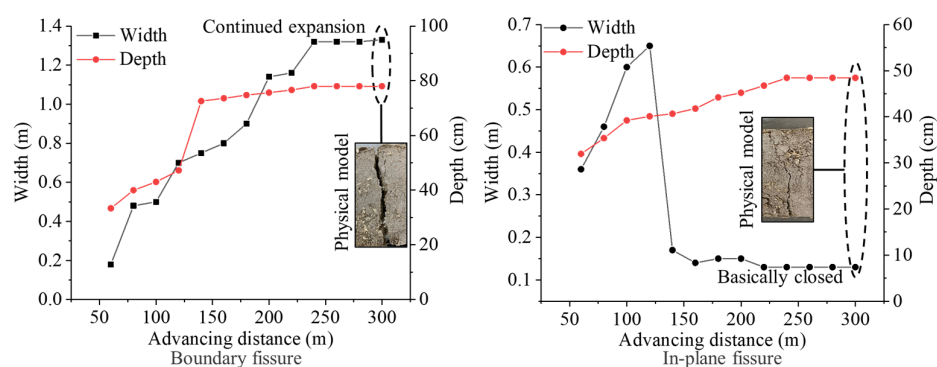


Figure 11. Part of the fissure width and depth variation.

For in-face fissures, influenced by the periodic dynamic alternation of tensile and compressive zones induced by working face advance, their width exhibits a distinct three-stage evolutionary pattern: initial increase—subsequent decrease—final stabilization. During the initial advancement stage (50–120 m), tensile action dominates, driving a rapid width increase from 0.36 m to a peak of 0.65 m. In the middle stage (120–240 m), the intensifying extrusion effect of the expanding compressive zone counteracts tensile growth, causing the width to decrease gradually, though the rate of decrease flattens with increasing advancement. By the late stage (240–300 m), the width stabilizes at 0.13 m. While fissure depth generally increases with advancement, it shares a significant synergistic correlation with width variation: the depth rises rapidly from 32 cm to 40 cm in the initial stage, but its growth rate slows markedly in the middle and late stages, eventually stabilizing at 48 cm. The morphological evolution of fissures in the physical model—documenting their transition from initial formation to dynamic development and eventual gradual stabilization—visually corroborates the width variation characteristics of boundary fissures (driven by sustained tensile stress) and in-face fissures (induced by alternating tensile-compressive stress). This provides robust quantitative empirical evidence for elucidating the evolutionary mechanism of mining-induced fissures.

3.2. Classification and Risk Assessment of Mining-Induced Fissures

To enhance the engineering guidance of this study, ground fissures are categorized into three primary types based on their morphological and mechanical behavior. Their respective risks to the environment and engineering safety are summarized as follows:

Tensile fissures (Open/Superficial): These fissures originate from surface tensile stress at the boundaries of the subsidence basin. They are characterized by large widths (up to 1.32 m) but shallow depths, typically remaining within the soil layer. Their primary risk is accelerated soil erosion and localized vegetation damage.

Step fissures (Dislocating/Semi-penetrating): These arise from the localized instability of the “virtual auxiliary arch,” leading to vertical strata dislocation. With step heights reaching up to 680 mm, they pose a significant threat to surface infrastructure such as roads and pipelines.

Collapse fissures (Penetrating): These represent the most severe form of damage, driven by the global instability of the “virtual main arch.” These fissures penetrate through the entire overburden, connecting with the water-conducting fissure zone (158 m height). They constitute high-risk hydrogeological channels that escalate the danger of mine water inrush (Table 3).

Table 3. Risk characterization of different ground fissure types.

Fissure Type	Mechanical Origin	Penetration Depth	Environmental Risk	Engineering Risk
Tensile	Surface tension	Shallow (soil)	High (soil erosion)	Low (surface cracking)
Step	Local dislocation	Moderate (subsurface)	Moderate (runoff alteration)	High (infrastructure damage)
Collapse	Global instability	High (to goaf)	Very High (water loss)	Critical (water/sand inrush)
Dynamic	Alternating stress	Temporary	Low (self-healing)	Low (temporary disturbance)

This differentiated risk framework allows for the implementation of targeted prevention strategies, such as focusing backfilling efforts on penetrating collapse fissures to protect groundwater resources while utilizing land leveling for superficial tensile fissures.

3.3. Evolution Characteristics of Overlying Strata Failure

Figure 12 illustrates the overlying strata failure characteristics following the mining of the No. 6-1 and No. 6 coal seams. The left-side borehole television image provides an intuitive visualization of geological anomalies at various depths: an initial fracture zone is marked at 2.0 m (showing the first transverse fissure), while irregular dark collapse zones—enclosed by red ellipses to indicate voids—appear at 57.1 m, 113.9 m, 124.8 m, 177.2 m, and 185.2 m. Notably, the 57.1 m void is the first to form due to rock mass collapse, and the subsequent continuous appearance of voids at deeper depths (113.9 m, 124.8 m, etc.) confirms the extensivity and high density of overlying strata fracturing. The right-side flushing fluid consumption curve—plotted with depth on the vertical axis and consumption on the horizontal axis—exhibits a stage-wise variation with increasing depth. Consumption increases significantly when drilling reaches 118.2 m, peaking at 5 m³/h, and a persistent leakage channel remains thereafter. Even when the final borehole water level drops to 193.0 m, the leakage persists, indicating that the water-conducting channel has penetrated to shallow depths. Although the flushing fluid consumption at the marked positions of the No. 3, No. 6-1, and No. 6 coal seams is lower than the peak leakage rate, it remains higher than the initial background level, reflecting an active water-conducting fissure zone near the coal seams.

Combined with the drilling process record (total footage: 212.2 m), fissure propagation and cavity development are continuously observed at multiple depths, notably in the 61.3~62.2 m and 85.9~173.0 m intervals. Cavity groups form, with fissures and cavities concentrated in the 177.2~185.7 m section; shallow intervals (e.g., 6.1~6.6 m, 19.0~19.5 m) also exhibit fissures, indicating a fracture network penetrating from shallow to deep strata. At the hole bottom, the water level plummets to 193.0 m, and the entire hole leaks. Notably, flushing fluid consumption persists at 194.6 m (near the coal seam), confirming that the

water-conducting fissure zone extends to the surface. In summary, after mining the No. 6-1 and No. 6 coal seams, overlying strata failure is dominated by dense fracture development and extensive cavity formation. The fracture density is high, and the fragmentation degree is significant (the caving zone extends below the No. 3 coal floor). The water-conducting fissure zone develops to the surface (with a continuous leakage hole to the final hole and a sharp water level drop of 193.0 m), and rock strata movement exhibits a “two-zone” mode. These findings verify the strong heterogeneous fracture characteristics of medium-hard rock strata. Based on the parameters of the 615 working face, the numerical results for the ultimate spans of thick, hard rock strata are calculated. For initial fracturing, the ultimate tensile span is 14.2 m and the shear span is 18.6 m. This confirms that tensile failure initiates earlier than shear failure in the study area.

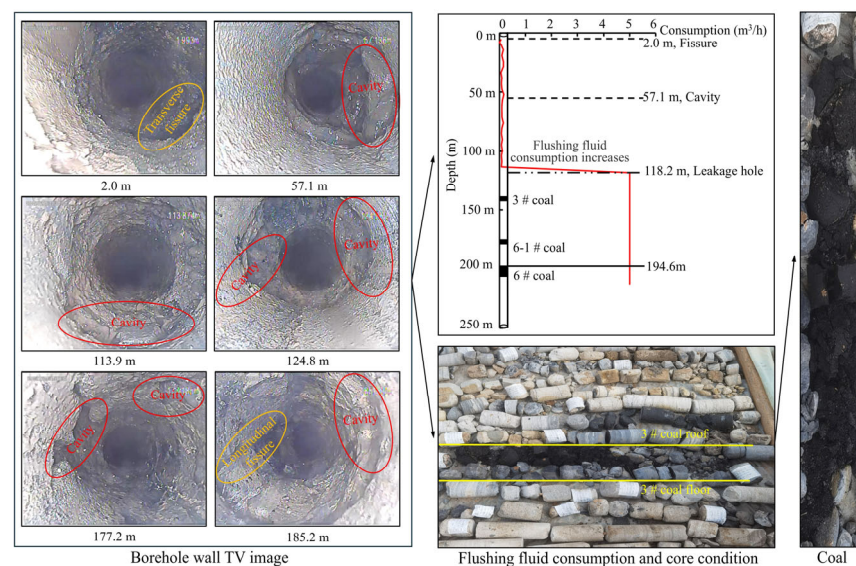


Figure 12. Water-conducting fissure zone height and core condition.

The practical implications of mining-induced damage in the Ordos Basin are directly governed by the magnitude of the measured fissure parameters. Table 4 synthesizes the correlation between our quantitative results and their corresponding environmental and engineering risks.

Table 4. Mapping of quantitative results to practical environmental and engineering risks.

Quantitative Result	Measured Value	Practical Problem	Risk Level	Impact Description
Fissure width	1.1~1.3 m	Soil degradation	High	Soil moisture loss and topsoil erosion
Step height	450~680 mm	Infrastructure threat	Critical	Damage to roads, pipelines, and buildings
Fissure zone height	158 m	Water infiltration	Critical	Groundwater depletion and water/sand inrush
Caving zone height	42 m	Strata instability	High	Violent roof weighting and strata dislocation

- (1) Field measurements identify a fissure zone height of 158 m. Given the shallow burial depth of the 615 working face, the “longitudinal penetration zone” occupies approximately 80% of the overlying strata thickness. This quantitative result confirms that collapse fissures act as direct conduits, facilitating the rapid downward infiltration of surface runoff and groundwater into the goaf, which depletes local water resources and threatens mine safety.
- (2) The maximum step height of 680 mm measured at the surface significantly surpasses the deformation tolerance of local infrastructure. For example, local hardened roads and brick-concrete structures in the Ordos Basin typically fail when vertical disloca-

tions exceed 200 mm. Our quantitative data explain why the step fissures observed in the study area lead to the immediate structural cracking and functional failure of surface roads and utility foundations.

- (3) The maximum fissure width of 1.32 m triggers severe soil degradation. Such extensive openings accelerate the evaporation of soil moisture and cause the localized collapse of the topsoil structure, leading to a 45% increase in soil erosion rates compared to undisturbed areas.

Figure 13 reveals the spatiotemporal evolution characteristics of overlying strata failure during the working face advancing process through a central profile and four Figure 13a–d. With the rightward arrow indicating the advancing direction, the central profile is sequentially divided into three failure zones: “caving zone,” “fissure zone,” and “longitudinal penetration zones I/II/III.” Combined with the working face breaking angle and the “two zones” height, the complete expansion process of the overlying strata failure range from a “non-isosceles trapezoid (0~140 m)” to an “isosceles trapezoid (140~300 m)” is presented. During the immediate roof caving stage (working face advanced 80 m, corresponding to Figure 13a), caved rock blocks exhibit a disordered wedge-shaped accumulation due to initial stress release, with longitudinal fissures extending obliquely upward along the dip direction of the rock strata, traversing the shallow caving zone. Restricted by breaking energy, the overlying strata failure range presents a “non-isosceles trapezoid” profile (short side facing the advancing direction), and the fissure zone is confined to the near-field region. At the primary breaking stage of the sub-thick hard rock strata (working face advanced 140 m, corresponding to Figure 13b), the broken rock blocks gradually regularize during the periodic “rotation-sliding” motion and develop a separation layer at the upper part. At this point, the fissure zone expands rapidly toward the deep part, and the overburden fissures extend both obliquely and laterally, transitioning the overlying strata’s failure range from a “non-isosceles trapezoid” to a symmetric “isosceles trapezoid.” The rock block rotation-induced broken rock accumulation zone in Figure 13b confirms the periodicity and symmetry of rock strata motion during this stage.

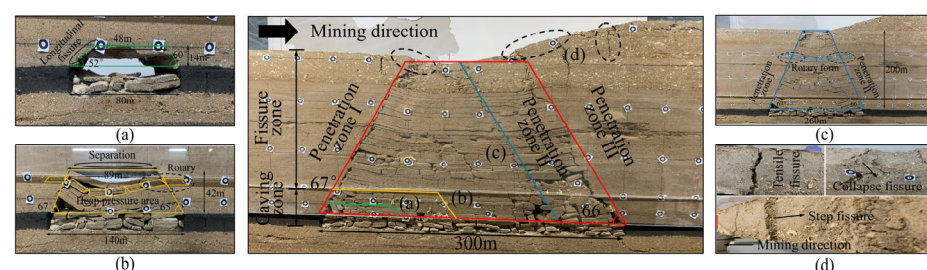


Figure 13. Overlying strata failure evolution characteristics (a) 80m; (b) 140m; (c) 260m; (d) ground fissures.

The primary breaking stage of the main thick, hard rock strata (working face advanced 260 m, corresponding to Figure 13c,d) is a critical node for mining-induced effects to propagate to the surface. Figure 13c shows that the overlying strata on the advancing side of the working face undergo through-going breaking, with the fissure network extending sharply toward the surface. Figure 13d captures the diversity of surface responses—overlying strata fissures connect with ground fissures to form longitudinal fissure penetration zones, inducing three typical surface damages: (1) tensile fissures oriented perpendicular to the vertical stress direction; (2) collapse fissures caused by differential settlement; (3) step fissures resulting from the stepwise displacement of rock strata. At this stage, the caving zone height is 42 m, and the fissure zone height is 158 m, marking the end of the full-range expansion of overlying strata failure. The rock block rotation trajectory in Figure 13 and

the multi-scale response of the macroscopic failure zones, combined with the consistency between the quantitative results and field-measured data, further verify the core characteristics of overlying strata failure under high-intensity mining: high fracture density and severe fragmentation.

4. Discussion

4.1. Mechanical Mechanism and Failure Mode Sensitivity

The selection of the tensile–shear failure mechanism as the primary driver for strata fracturing is intrinsically linked to the “deep beam” geometry prevalent in shallow-buried and thick seam mining. Unlike traditional “shallow beam” models, the deep beams in the Ordos Basin exhibit a stress distribution where horizontal and shear components are highly amplified relative to vertical compression. The sensitivity of the predicted fissure behavior to this assumption was evaluated by comparing the ultimate spans for different failure modes. The results indicate that tensile–shear failure consistently occurs at lower spans than those required for alternative mechanisms under the identified lithological combinations.

Furthermore, other mechanisms such as compressive buckling and creep were determined to be secondary in this specific high-intensity mining condition. Buckling is precluded by the substantial span-thickness ratio of the key strata, which favors brittle fracture over instability-induced bending. Similarly, the rapid advancing speed (4 m/d) minimizes the influence of creep on the initial development of ground fissures. While creep may contribute to the gradual closure of in-face fissures during the stabilization phase, the catastrophic formation of penetrating fissures—the primary focus of this study—is governed by the instantaneous mechanical response of the rock mass. Consequently, the tensile–shear assumption provides a reliable and representative framework for analyzing the co-evolution of rock strata failure and ground fissure development in the study area.

4.2. Theoretical Framework

4.2.1. Virtual Arch Support System

Virtual main and auxiliary arches are abstract equivalent support systems derived from the mechanical properties of rock strata, rather than visible physical structures. The virtual main arch corresponds to a self-stabilizing arch effect formed by thick, hard rock strata in the upper part, acting as a primary load-bearing structure. The virtual auxiliary arch functions as a transitional unit, transferring the overlying strata’s load from the middle rock strata to the underlying pressure-bearing body. The pressure-bearing body relies on the residual mechanical properties (e.g., compaction, residual support characteristics) of the remaining rock layers after coal mining to provide reverse support. Step fissures originate from the localized instability of the support system, specifically when mining reduces the bearing capacity of the virtual auxiliary arch below its critical threshold; the virtual auxiliary arch fails first. Owing to the residual self-stabilization capacity of the virtual main arch, the upper rock strata undergo stepwise dislocation along the equivalent interface between the virtual auxiliary and main arches (analogous to the stepwise descent of multiple tiers). During this process, tensile and shear stresses concentrate within the rock strata, forming regular step tensile/shear fissures. These fissures are confined to the vicinity of the failed virtual auxiliary arch zone and do not compromise the core of the virtual main arch.

Collapse fissures result from the instability of the entire support system: high-intensity mining leads to the complete failure of the pressure-bearing body. The virtual auxiliary arch, composed of extremely fragmented rock (e.g., shale, crushed sandstone), rapidly collapses under unloading, and the virtual main arch loses its self-stabilization arch effect due to the disappearance of the lower constraint. Eventually, the overlying strata enter a state of free collapse under gravity. During collapse, the rock strata undergo intense tensile, shear, and

impact fracturing, forming irregular collapse fissure networks. The difference between the two fissure types essentially reflects distinct instability manifestations of the rock strata's strength hierarchy and support system integrity under stress regulation. The key controlling variables are the mining-induced unloading range and the lithology of the underlying rock strata: the former exhibits localized dislocation and regular fissures, while the latter shows large-scale collapse and irregular fissures. Moreover, the more fragmented the rock lithology and the stronger the mining disturbance, the more pronounced this difference becomes (Figure 14).

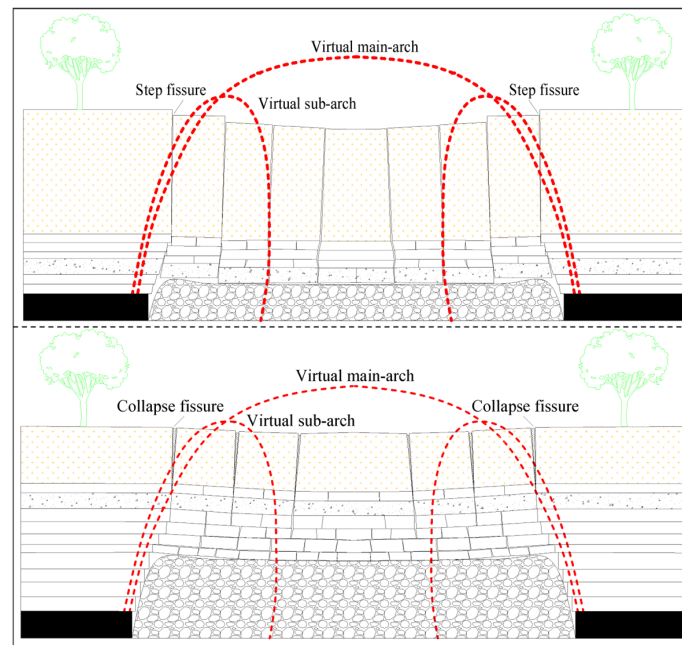


Figure 14. Formation mechanism of step and collapse fissures.

4.2.2. Principles for Determining Tensile and Extrusion Fissures

After coal mining, a subsidence basin forms on the surface. Along the strike and dip sections, the subsidence curve is demarcated by the inflection points of surface deformation into a tension zone and a compression zone (Figure 15). During working face mining, tensile fissures lag behind the working face development, while compression fissures advance ahead of it. The former is located in the surface tension zone, and the latter in the surface compression zone. When the horizontal deformation value in different zones exceeds the zone's ultimate tensile strain (for tension zones) or critical compressive deformation threshold (for compression zones), the surface develops tensile fissures and compression fissures, respectively. Therefore, determining the horizontal deformation value—particularly the ultimate tensile strain and critical compressive deformation threshold—is critical for predicting and controlling surface fissures in mining areas.

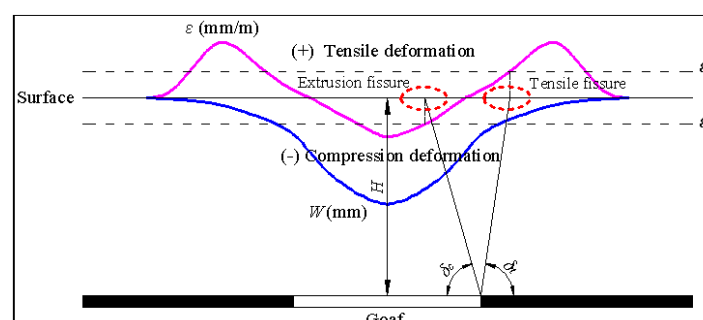


Figure 15. Formation process of tensile fissure and extrusion fissure.

4.3. Model Applicability and Research Significance

4.3.1. Model Applicability and Safety Considerations

The proposed mechanical models, including the deep beam and the “virtual main arch—virtual auxiliary arch” system, are based on the assumption of a homogeneous rock mass. However, actual overlying strata often contain heterogeneities such as joints, faults, and weak interlayers. These structural features can act as planes of weakness, potentially leading to localized deviations in the predicted fracture positions and the spatiotemporal evolution of fissures. For instance, pre-existing joints may trigger fracturing at stress thresholds lower than those calculated for a continuous beam, while weak interlayers can facilitate horizontal sliding that modifies the height of the “two zones”.

Despite these potential localized inaccuracies, the simplified homogeneity assumption is strategically valuable for elucidating the fundamental mechanical response of the strata-surface system. It provides a clear mechanical framework to judge the overall distribution types and failure modes of ground fissures. Specifically, the model identifies the mechanical thresholds that distinguish step fissures, which are driven by localized auxiliary arch instability, from collapse fissures, which result from the global instability of the support system. This macro-scale perspective enables a quantitative assessment of the gradient distribution effect, characterized as “strong disturbance in the near field and weak response in the far field”. Consequently, while the inclusion of micro-heterogeneities remains a priority for future high-precision modeling, the current theoretical framework serves as a reliable and actionable tool for the macro-scale evaluation and prevention of geological disasters in high-intensity mining regions.

The co-evolution mechanisms identified in this study are derived from the high-intensity mining conditions of the Ordos Basin, which serves as a representative prototype for shallow-buried, extra-thick coal seam mining conditions. Despite the site-specific nature of the empirical data, the underlying mechanical logic—the “virtual main arch—virtual auxiliary arch” theory—possesses significant generalizability. This equivalent support system framework characterizes the transition from localized instability to global failure, providing a transferable baseline for other global coal-mining hubs facing similar strata-surface co-damage challenges. The fissure types observed—tensile, step, and collapse—correspond to specific stress states within the overlying rock mass that are common across various geological settings. While regional factors such as the loess gully geomorphology or arid climates modulate the magnitude of fissure parameters, the fundamental failure modes are governed by the span-thickness ratio and the tensile-shear strength of the rock beams. Despite the core mechanical logic being transferable, its application to other geological settings requires the calibration of key parameters such as lithological strength and mining depth. To mitigate the risk of over-reliance on idealized models, it is crucial to recognize that these theoretical frameworks provide a macro-scale predictive baseline. Given the inherent uncertainty of rock mass behavior, the model should be integrated into an adaptive safety management framework that utilizes real-time monitoring data from the “space—air—ground—borehole” system to refine predictions. By identifying the mechanical thresholds for different fissure types (e.g., global support system instability leading to collapse fissures), the model provides actionable intelligence for disaster prevention while necessitating a conservative approach in engineering practice.

4.3.2. Research Significance

We have integrated multi-source monitoring data to substantiate the reliability of the proposed models. First, the discrete cavity and fissure development features captured via borehole television at depths such as 57.1 m and 113.9 m align closely with the fracture locations of thick, hard rock strata predicted by the deep beam model. Simultaneously,

the abrupt increase in drilling fluid consumption at 118.2 m and its subsequent penetration to the surface provide robust empirical support for the theoretical derivation of the longitudinal penetration zone induced by overlying strata failure.

Second, physical simulation results intuitively captured the “rotation-sliding” motion of rock blocks and the evolution of the failure scope from a “non-isosceles trapezoid” to an “isosceles trapezoid”. The observed spatial morphology of the caving zone, fissure zone, and longitudinal penetration zone validates the scientific rigor of the mechanical partitioning and penetration mechanisms within the “virtual main arch—virtual auxiliary arch” equivalent support system.

Finally, the measured gradient distribution of ground fissures—characterized by “strong disturbance in the near field and weak response in the far field”—along with the morphological features of tensile, step, and collapse fissures, exhibits high consistency with the mechanical calculation results derived from the local or global instability modes of the virtual support system. Compared with previous studies, this work excels in three key areas: (1) the monitoring method surpasses traditional single methods in data acquisition comprehensiveness; (2) the theoretical model improves applicability over shallow beam theory; (3) it fills the mechanical gap in the formation mechanisms of step and collapse fissures.

4.3.3. Research Comparison and Limitations

The patterns of ground fissure development identified in the Ordos Basin display distinct intensifications when compared to findings from previous studies (Table 5) [2–10]. The mining intensity (defined by the ratio of mining depth to mining thickness) and advancing speed serve as the primary drivers for variations in fissure geometry and density.

Table 5. Comparison of ground fissure characteristics under different mining intensities.

Parameter	High-Intensity Mining (This Study)	Conventional Mining (Previous Studies)	Influence of Intensity
Fissure width	1.1~1.3 m	0.2~0.5 m	Significant expansion
Step height	680 mm	100~250 mm	Extreme dislocation
Fissure length	180~250 m/hm ²	30~100 m/hm ²	High-density network
Primary mechanism	Global arch instability	Localized surface tension	Transition to system failure

Fissure Geometry and Density: Under high-intensity mining (>4 m/d), the stabilized fissure width (1.32 m) and maximum step height (680 mm) exceed the values typically reported for conventional longwall mining in the Appalachian Basin or Upper Silesia, where widths generally remain below 0.5 m and step heights seldom surpass 200 mm. Furthermore, the fissure length observed in this study (210 m/hm²) is significantly higher than the 40–90 m/hm² reported for lower-intensity mining [2,3,6–10].

Development Mechanisms: Previous research often relies on key stratum theory and voussoir beam theory to describe strata failure [13–18]. However, our results indicate that for the shallow-buried, thick-seam conditions of the Ordos Basin, the “virtual main arch—virtual auxiliary arch” theory provides a more accurate mechanical characterization. While traditional studies attribute fissures to simple surface tension, our framework reveals that high-intensity mining triggers a global support system instability, leading to the “penetrating collapse” fissures that are rarely observed in lower-intensity settings. This comparative evidence confirms that high-intensity mining results in a “gradient intensification” of ground disasters, necessitating the targeted mitigation strategies discussed in the preceding sections.

Despite the above progress, several limitations warrant attention for future work. First, the spatiotemporal resolution of monitoring data requires enhancement. Although UAV images achieve a 5 cm/pixel resolution, this remains insufficient for capturing millimeter-scale fissures. Moreover, the monitoring period primarily covers the working face advancement stage (0–300 m), with no data on long-term subsidence effects. For instance, while fissure width data reveal dynamic development characteristics, the limited sampling frequency may miss short-term fluctuations—echoing the emphasis on long-term monitoring in Reference [5]. Second, the homogeneous rock property assumption in the theoretical model does not fully account for the heterogeneity of actual rock strata (e.g., joints and soft interlayers), potentially leading to deviations in predicting fracturing positions. Although physical models can replicate the macro-distribution types of ground fissures, they struggle to simulate the micro-fracture propagation within rock masses [10]. Third, the study is conducted in the arid climate and loess gully geomorphology of the Ordos Basin, where ground fissure development is inevitably coupled with climate and topography. These limitations highlight key directions for future research: improving high-precision monitoring technologies, refining theoretical models under heterogeneous conditions, and conducting multi-region comparative studies.

5. Conclusions

This study integrates in situ monitoring data with theoretical models to address the defined mechanistic objectives. The outcomes demonstrate a direct causal link between internal rock strata failure and surface damage patterns:

- (1) A mechanical model for thick, hard rock strata fracturing under shallow thick coal seam conditions is established, revealing that rock beams exhibit compound tension–shear failure during both initial and periodic fracturing. Horizontal and shear stress increase significantly with the span-thickness ratio. The ultimate span is determined by beam thickness and material strength but negatively correlated with load. Due to the mudstone-sandstone lithology, fissure trajectories are approximately linear, and the orientation angle is negatively correlated with the rock mass friction coefficient.
- (2) Ground fissures manifest spatial differentiation: tensile fissures concentrate in mining stress concentration areas, step fissures are controlled by rock strata dislocation, and collapse fissures appear in high-stress or low-integrity areas. The fissure disaster shows a gradient effect of “strong disturbance in the near field and weak response in the far field”. The overlying strata failure is characterized by non-uniform features of dense fissure development and extensive cavity formation, which can be divided into caving, fissure, and longitudinal penetration zones.
- (3) Tensile Fissures originate from concentrated tensile stress in surface tension zones. Prevention strategies focus on sealing these fissures to mitigate soil erosion and subsurface water infiltration. Step Fissures arise from localized instability of the virtual auxiliary arch, leading to differential sliding. Guidance involves monitoring topographic abruptness and implementing land leveling for surface restoration. Collapse Fissures result from global instability where the virtual main arch loses its self-stabilization effect. Safety protocols prioritize establishing near-field exclusion zones and reinforcing infrastructure.
- (4) The innovative “virtual main arch—virtual auxiliary arch” equivalent support system theory elucidates the formation mechanisms of different fissure types. Step fissures arise from local support system instability, while Collapse fissures result from overall support system instability. The mechanical framework provides a robust theoretical basis for the prediction and prevention of mining-induced fissure disasters.

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