ISSN: 2637-6067 DOI: 10.6918/IJOSSER.202608_9(8).0008

Application of 3DEC Numerical Simulation Method in Experimental Teaching of Mine Safety Engineering

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Abstract

An in-depth understanding of mining models, the mining-induced evolution characteristics of three-dimensional principal stresses, as well as stress states and instability failure modes, is critical for students to grasp the disaster-causing mechanisms of roof disasters, gas disasters, water inrush disasters and other hazards in mine safety engineering. Compared with the traditional mechanical analytical method, field in-situ stress test data analysis method and triaxial compression test method, the 3DEC numerical simulation method can characterize the stress distribution and failure morphology during mining more accurately. It possesses advantages such as high consistency with engineering practice, strong teaching visualization and low experimental cost. Taking the N00 mining method for longwall mining as the research object, this study adopts a teaching approach combining theoretical analysis and 3DEC numerical simulation to systematically reveal the mechanical response characteristics of rock masses at key positions under this mining method. The results show that: (1) In view of the mechanical property that rock masses resist compression but are vulnerable to tension, the directional hydraulic roof cutting technology can realize hydraulic fracture generation with low disturbance. (2) Under the combined effect of cutting fractures and mining disturbance, the three-dimensional principal stresses of immediate roof rock blocks on the goaf side present a dynamic evolution characteristic of "increase–decrease–increase", accompanied by obvious deflection of mining-induced principal stress directions. (3) The mining-induced failure mode of roof rock blocks on both sides of the goaf is tension-shear composite failure, while that in the central area is shear failure. Teaching practice demonstrates that introducing the 3DEC numerical simulation method into the experimental teaching of mine safety engineering is highly feasible. This method enriches teaching approaches and provides effective research methods and implementation paths for students to understand the mechanisms of engineering disasters.

Keywords

Mine safety engineering; N00 mining method; experimental teaching; principal stress evolution; 3DEC numerical simulation.

1. Introduction

Energy security and its high-quality development constitute critical challenges related to sustainable development facing China at present. Coal resources act as the ballast stone for guaranteeing the stable supply of national energy security[1]. Mine Safety Engineering covers the disaster-causing mechanisms, influencing factors, evolution laws, prevention and control technologies, as well as emergency disposal of typical engineering geological hazards occurring in coal mining, such as roof disasters, gas hazards, water inrush and engineering slope landslides. It serves as an important fundamental professional course for majors including Emergency Technology and Management, Emergency Management, Safety Engineering and

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Mining Engineering. Understanding mining models, the dynamic evolution law of three-dimensional principal stresses during mining, stress states and instability failure modes is the key for students to master the initiation process and disaster-causing mechanisms of the aforementioned hazards. Nevertheless, the existing teaching methods still have certain limitations in theoretical depth, engineering suitability and teaching effectiveness.

At present, in practical teaching, the learning of the above mechanical indicators mainly adopts mechanical analytical methods, field in-situ stress test data analysis methods, triaxial compression test methods.

1) The mechanical analytical method highly relies on students' in-depth command of Mechanics of Materials, Elastoplastic Mechanics and Rock Mechanics, and requires a sound spatial imagination, leading to high learning difficulty[2]. Meanwhile, this method has inherent deficiencies: (1) It assumes rock mass to be continuous, isotropic and homogeneous material[3,4], which obviously contradicts the prominent discontinuity, anisotropy and heterogeneity of natural rock masses; (2) The analytical results obtained are a set of static data, whereas the magnitude and direction of three-dimensional principal stresses continuously change under mining disturbance during actual production; (3) It supposes that the three principal stresses at any point within rock mass are mutually perpendicular, which conflicts with field measurement results.

2) Among field in-situ stress testing methods, hydraulic fracturing[5] and hollow inclusion strain cell method[6,7] are widely adopted. The hydraulic fracturing method is based on plane stress theory and relies on three assumptions: (1) The rock mass is a homogeneous and isotropic elastic medium; (2) Rock is impermeable; (3) One principal stress direction is parallel to the borehole axis. The hollow inclusion method is theoretically derived from the analytical solution for three-dimensional in-situ stress around a borehole in an infinite elastic medium in elastic mechanics, and the measured data are more consistent with engineering practice. However, data acquired via in-situ stress tests are static values at discrete points, which can hardly visually demonstrate the dynamic evolution law of stress in the mining process.

3) The triaxial compression test method[8,9] is commonly used to determine fundamental rock mechanical parameters of rock specimens, such as triaxial compressive strength, cohesion and internal friction angle. Strength envelopes can be obtained through a series of triaxial compression tests under different confining pressures, which is of great significance for understanding rock mass failure processes. However, experimental conditions differ greatly from real mining environments. It is generally presumed that loading directions correspond to the three principal stress directions, which brings deviations from practical engineering conditions.

None of the above methods can satisfy students' demands for an in-depth understanding of the dynamic evolution of mining-induced three-dimensional principal stresses and rock mass fracture mechanisms, thus impairing their learning outcomes regarding prevention and control technologies for disasters such as roof hazards and coal and gas outbursts. In contrast, the 3DEC distinct element numerical simulation method fully considers random joints, anisotropy, heterogeneity and discontinuity of rock masses. It can realistically simulate the temporal and spatial variation of mechanical indicators such as stress, displacement and failure type of arbitrary units during coal mining. Additionally, it has advantages of high engineering consistency, strong visualization and low experimental cost.

On this basis, this study selects the N00 longwall mining method, representing the third technological revolution in coal mining methods[10], and carries out experimental teaching reform exploration combining theoretical analysis with 3DEC numerical simulation. The main contents are as follows: (1) Introduce the key technology of the N00 longwall mining method, i.e., directional hydraulic fracturing roof cutting technology; (2) Based on DFN random joints,

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investigate the dynamic evolution characteristics of mining-induced three-dimensional principal stresses at arbitrary points in the goaf beside the automatically formed roadway under the combined influence of cutting fractures and mining disturbance; (3) Identify fracture and instability modes of rock masses at different positions in the goaf. By integrating 3DEC distinct element numerical simulation with theoretical teaching, this study aims to improve students' cognition of mine disaster mechanisms induced by rock mass fracture and instability, and provide new ideas for the experimental teaching of the course Mine Safety Engineering.

2. N00 Longwall Mining Method and Its Key Technologies

The mining model serves as the structural basis governing the mining-induced evolution characteristics of three-dimensional principal stresses. Accordingly, the layout of the N00 longwall mining method, structural features of the automatically formed roadway, and the directional hydraulic roof cutting method are demonstrated to students, laying a foundation for them to understand the coupling relationship between mining-induced three-dimensional principal stress evolution and mining models.

2.1. Layout of the N00 Longwall Mining Method

The N00 longwall mining method was proposed by Academician He Manchao on the basis of the roof-cutting short cantilever beam theory[11-13]. This technology adopts roof cutting for pressure relief and makes full use of mine pressure. The broken and dilated gangue generated by roof caving forms the gangue rib of the gob-side entry, which eliminates the need for roadside backfilling and reduces the mine pressure acting on the gob-side entry[14-16]. It fundamentally addresses the severe mine pressure behavior and uncontrollable surrounding rock deformation of gob-side entries.

The schematic layout of the N00 longwall mining method is shown in Figure 1. Compared with the conventional longwall mining method, its core innovation lies in that no pre-drivage of roadways on both sides of the working face is required; the entries are automatically formed during mining by means of roof cutting and pressure relief.

The N00 longwall mining method changes the panel layout of traditional mining approaches, which can be summarized as follows:

(1) A return air dip, belt dip and track dip are arranged within a new panel. The return air dip and track dip are located at one end of the panel, while the belt dip connects the other end and communicates with the return air dip via connecting roadways.

(2) The working face is deployed inside the panel enclosed by the above roadways. One side of the working face is a pre-excavated entry, and the other side is an entry automatically formed during mining utilizing roof cutting pressure relief technology and mine pressure.

(3) The working face adopts the Z-type ventilation[17,18].

2.2. Structural Characteristics of the N00 Longwall Mining Method

Compared with roadways in conventional longwall mining, the automatically formed roadway generated by the N00 mining method possesses distinctive structural characteristics, as illustrated in Figure 2: (1) The solid coal rib of the automatically formed roadway is arc-shaped rather than vertical as seen in conventional working faces. (2) The gangue rib of the automatically formed roadway consists of caved and dilated gangue, instead of the roadside backfilling structure commonly adopted in traditional gob-side entry retaining. (3) A regular cutting fracture exists in the roof. (4) The coal mass forming the automatically formed roadway is cut by a shearer, whereas roadways in the other two mining methods are excavated via roadway drivage.

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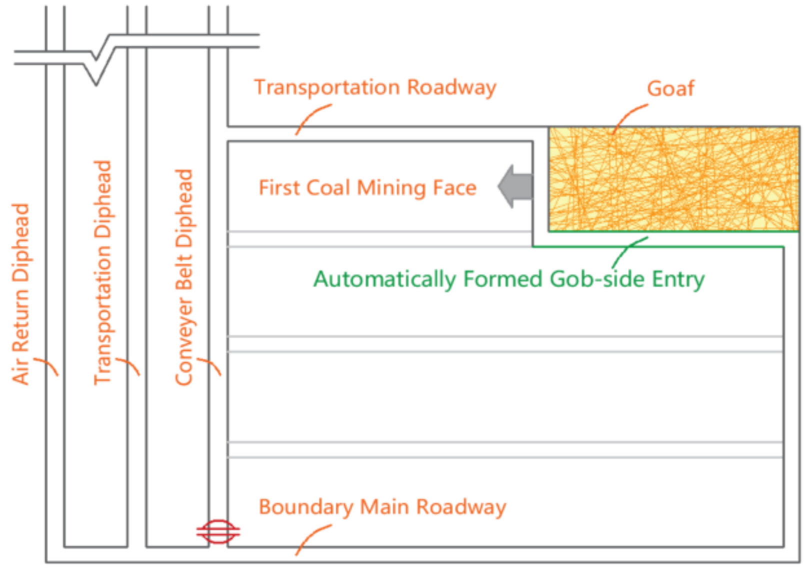

Figure 1. Layout of the N00 longwall mining method

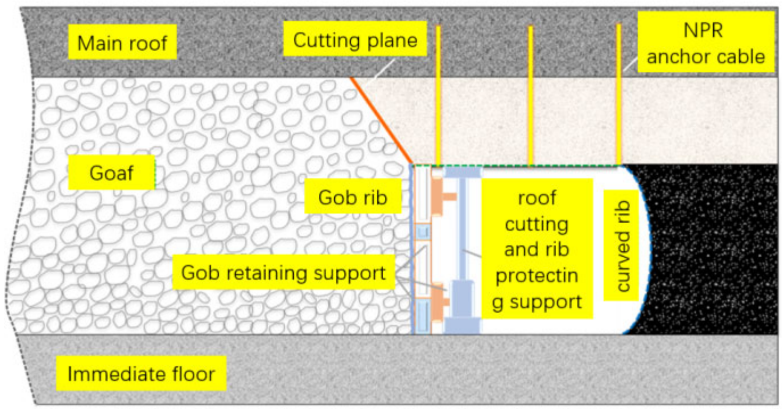

Figure 2. Structural Characteristics of Automatically Formed Roadway for N00 Mining Method

2.3. Directional Hydraulic Roof Cutting Method

Roof cutting constitutes the key to the formation of automatically formed roadways and determines the success of the N00 longwall mining method. To avoid severe disturbance to roof rock mass induced by explosive blasting cutting, directional hydraulic fracturing technology is adopted for roof cutting in the N00 longwall mining method.

1) Principle of Directional Hydraulic Roof Cutting Technology

The directional hydraulic roof cutting technology employs high-pressure water jet technology to directionally generate cutting slots along cutting boreholes in rock masses. Cutting slots formed in adjacent boreholes connect and penetrate each other to form a neat cutting plane.

During cutting construction, water is pressurized by a high-pressure pump to form high-pressure water. Abrasives are mixed into the water via an abrasive feeding device. The mixture flows through high-pressure explosion-proof hoses and high-pressure sealed drill pipes into the delivery unit, then passes through high-pressure sealed drill pipes and finally generates cutting fractures via the fracture maker (nozzle) to realize directional fracture initiation. The detailed operation procedures are as follows: Firstly, pre-drill cutting boreholes in roof strata. Subsequently, install fracture makers (nozzles) directionally inside the cutting boreholes by using the delivery unit and high-pressure sealed drill pipes. High-pressure water jets are used to create fractures radially from the cutting boreholes toward adjacent boreholes, which directionally connect all cutting boreholes and form directional fracture planes.

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2) Advantages of Directional Hydraulic Roof Cutting Technology

By developing matched equipment for directional hydraulic roof cutting, the directional hydraulic roof cutting technology performs directional cutting within prearranged roof cutting boreholes based on the cutting mechanism of high-pressure water jets. This technology inherits the merits of conventional high-pressure water jet technology, including concentrated energy transmission, spark-free operation and effective dust suppression. Meanwhile, it fully incorporates the directional cutting concept adopted in the bidirectional energy-gathered tensile blasting method, enabling directional fracture generation along predetermined directions.

3. Engineering Background and Numerical Simulation Model

Compared with hypothetical engineering backgrounds, real engineering backgrounds can immerse students in practical scenarios and thus improve teaching effectiveness. Based on the field conditions of the S12012 working face adopting the N00 longwall mining method in Ningtiaota Coal Mine, a 3DEC distinct element numerical simulation model is established.

3.1. Engineering Background

The layout of the S12012 working face with the N00 longwall mining method is shown in Figure 3. The S12011 working face adopts the conventional longwall mining method, while the S12012 working face is the first working face applying the N00 mining method at home and abroad.

Based on the geological investigation reports: (1) The coal seam thickness of the S12012 working face ranges from 4.04 m to 4.35 m. (2) The immediate roof is siltstone with a thickness of 0.78 m, or a composite stratum consisting of 4.05 m-thick siltstone and 4.50 m-thick sandy mudstone. (3) The main roof is medium-grained sandstone with a thickness of 16.2–18.6 m. (4) The immediate floor is siltstone with a thickness of 4.4 m. (5) The main floor is fine-grained sandstone with a thickness of 3.2–19.6 m.

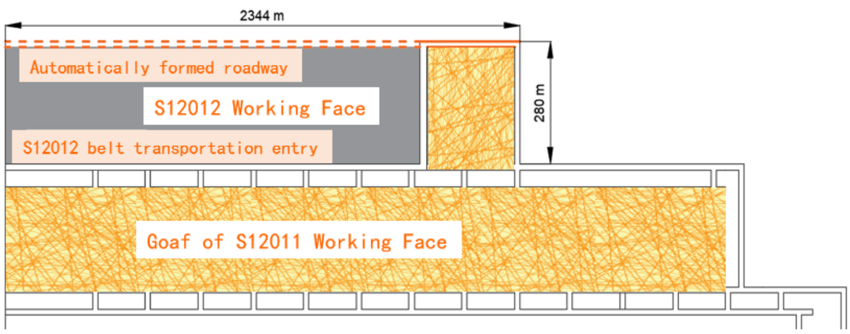

Figure 3. Layout of S12012 Working Face with N00 Mining Method

3.2. Numerical Simulation Model

A numerical model for the S12012 working face is established by combining DFN random joints and artificial joints, as shown in Figure 4. The burial depth is 170 m, and the model dimensions are length × width × height = 190 m × 150 m × 121 m. Displacement constraints are applied to the left, right, front, rear and bottom boundaries. The average unit weight of strata is set to 25 kN/m^3, and a vertical stress of 1.25 MPa is applied on the upper boundary of the model. The Mohr-Coulomb strength criterion is adopted as the failure criterion during excavation.

The inclined length of the working face is 140 m with a nearly horizontal dip angle. Both the original roadway on the left and the automatically formed roadway on the right have a width of 3.8 m and a height of 3 m. According to the geological data provided by Ningtiaota Coal Mine, the rock mass strength of the S12012 working face is approximately 57% of intact rock strength.

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The physico-mechanical parameters used in this simulation are determined accordingly, and the detailed values are listed in Table 1.

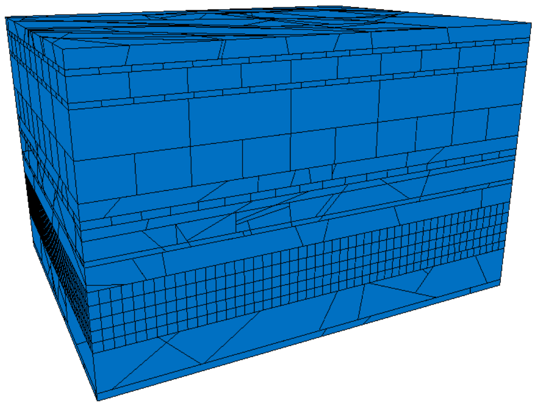

Figure 4. Numerical Model of S12012 Working Face

Table 1. Rock Mechanical Parameters

Lithology	Density (kg/m3)	Bulk Modulus (GPa)	Shear Modulus (GPa)	Cohesion (MPa)	Internal Friction Angle (°)	Tensile Strength (MPa)
Fine-grained sandstone	2320	8.99	7.31	1.00	38.42	0.48
Siltstone	2410	10.23	8.33	1.17	40.81	0.70
Coal seam	1260	3.95	3.22	1.05	39.69	0.78
Medium-grained sandstone	2280	5.46	4.27	0.69	41.33	0.33
Coarse-grained sandstone	2290	5.26	4.29	1.32	40.38	1.21
Sandy mudstone	2410	5.45	4.69	1.38	41.33	1.25

4. Dynamic Evolution Characteristics of Mining-Induced Three-Dimensional Principal Stresses

Rock masses in the goaf beside the automatically formed roadway are selected as research objects. The target rock mass is located 30 m ahead of the cutting plane, and the magnitude and orientation characteristics of its three principal stresses during working face advancement are investigated.

4.1. Variation Characteristics of Three-Dimensional Principal Stress Magnitudes

To demonstrate the numerical variation of three-dimensional principal stresses induced by mining disturbance to students, principal stress data are extracted at working face advance distances of 0 m, 3 m, 6 m, 9 m, 15 m, 21 m, 30 m, 45 m and 60 m. Variation curves of three-dimensional principal stresses under different advance distances are plotted, as shown in Figures 5–7.

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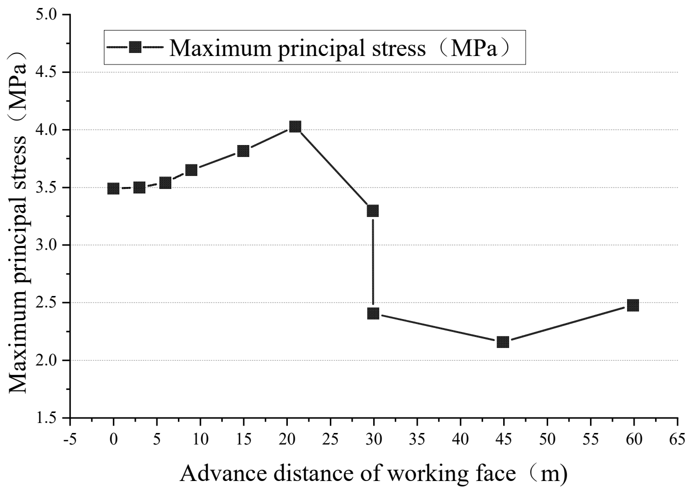

Figure 5. Variation Curve of Maximum Principal Stress

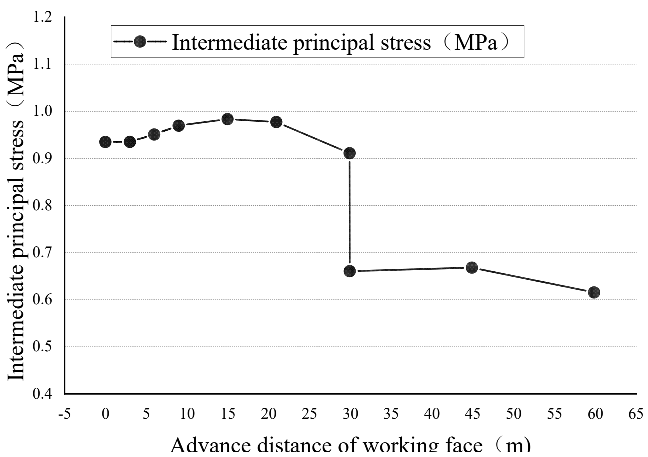

Figure 6. Variation Curve of Intermediate Principal Stress

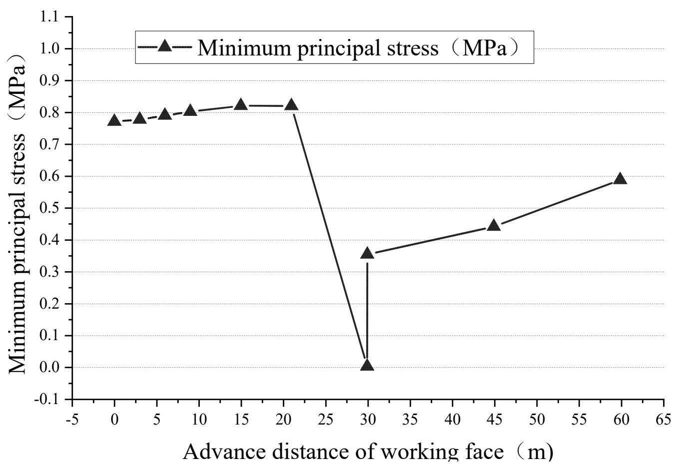

Figure 7. Variation Curve of Minimum Principal Stress

It can be seen from the figures that the magnitudes of the three principal stresses change continuously with working face advancement: (1) When the working face advances from 0 m to 21 m, all three principal stresses rise to varying degrees under mining-induced stress. The increase amplitude follows the order: maximum principal stress > minimum principal stress > intermediate principal stress. (2) As the working face advances from 21 m to 30 m, all three principal stresses drop remarkably accompanied by fluctuation. The reduction amplitude

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follows the order: minimum principal stress > maximum principal stress > intermediate principal stress. (3) When the working face advances from 30 m to 60 m, both the maximum and minimum principal stresses increase, while the intermediate principal stress decreases first and then rises.

4.2. Variation Characteristics of Three-Dimensional Principal Stress Orientations

The orientations of three principal stresses are represented by the angles between principal stresses and the Y-Z, X-Z, X-Y planes. Curves illustrating the orientation evolution of three-dimensional principal stresses at working face advance distances of 0 m, 3 m, 6 m, 9 m, 15 m, 21 m, 30 m, 45 m and 60 m are shown in Figures 8–10.

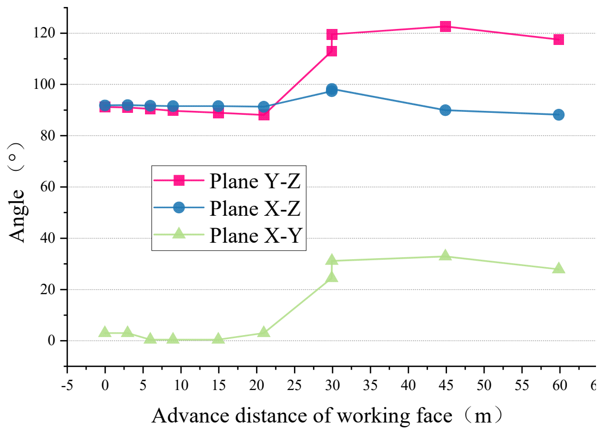

Figure 8. Rotation Curve of Maximum Principal Stress Orientation

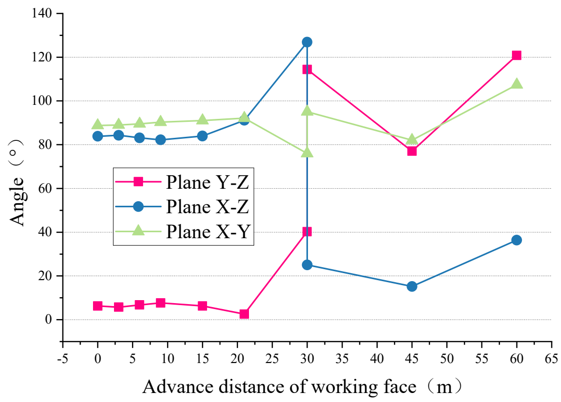

Figure 9. Rotation Curve of Intermediate Principal Stress Orientation

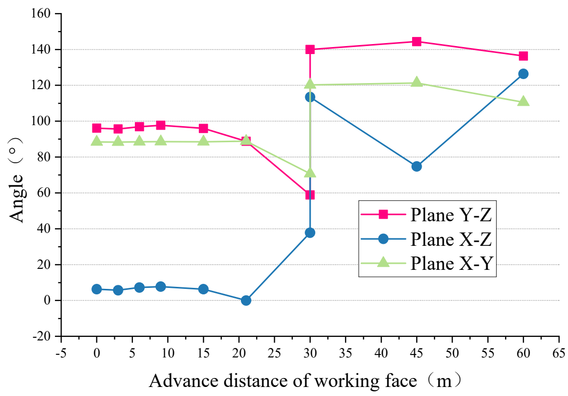

Figure 10. Rotation Curve of Minimum Principal Stress Orientation

It can be observed from the figures that: (1) The orientations of the three principal stresses undergo slight changes when the working face advances from 0 m to 15 m. (2) As the working face advances from 15 m to 21 m, principal stress orientations start to change, and the variation trends of the angles between principal stresses and each plane differ from one another. (3) Under the action of mining-induced stress during working face advancement from 21 m to 30 m, severe deflection occurs in all three principal stress orientations, accompanied by remarkable changes in the angles between principal stresses and each plane. (4) When the working face advances from 30 m to 60 m, the orientation of the maximum principal stress remains relatively stable. The angles between the intermediate principal stress and each plane decrease first and then increase, whereas the minimum principal stress presents inconsistent variation trends.

5. Mining-Induced Stress State and Fracture Mode of Rock Mass

The 3DEC distinct element numerical simulation software can record the stress state of each point within the model. The roof rock mass in the goaf 30 m ahead of the cutting plane is selected as the monitoring point. Diagrams reflecting stress state characteristics under different mining layouts at the cutting side, central area and non-cutting side of the working face are plotted, as shown in Figures 11–13.

Different numbers in Figures 11–13 represent distinct stress states and evolutionary processes of stress states. Comparative analysis yields the following conclusions: (1) When the working face advances 21 m, the monitoring points at both ends of the goaf (cutting side and non-cutting side) remain in an elastic state, while shear yield occurs at the monitoring point in the central area of the working face. (2) When the working face advances 30 m, the monitoring point on the cutting side of the goaf is in a shear yield state; the monitoring point in the central area of the working face enters the failure state, and failure emerges earlier at this point than that on the cutting side. The monitoring point on the non-cutting side undergoes tensile failure, and tension-shear composite failure has already occurred at this point in the preceding mining stage. (3) When the working face advances 45 m and 60 m, the failure patterns of monitoring points at different positions in the goaf no longer change. The monitoring points at both ends of the goaf (cutting side and non-cutting side) exhibit a tension-shear composite failure mode, whereas the monitoring point in the central area presents a shear failure mode.

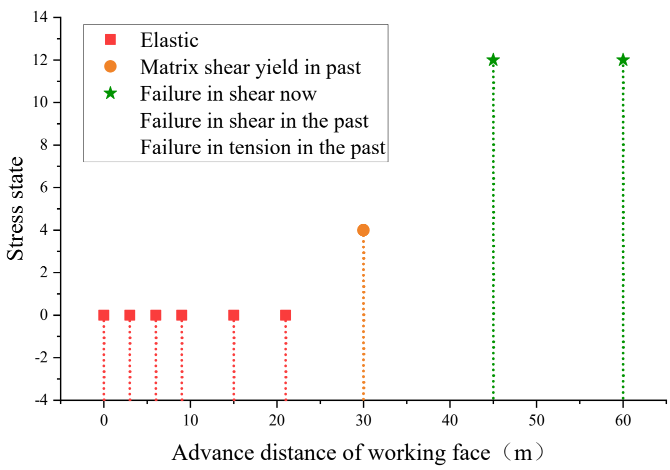

Figure 11. Evolution Characteristics of Stress State in Goaf on Cutting Side

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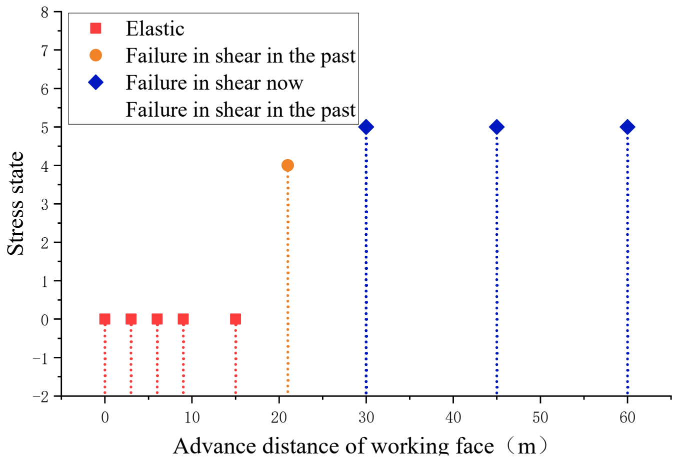

Figure 12. Evolution Characteristics of Stress State in Goaf at Working Face Central Area

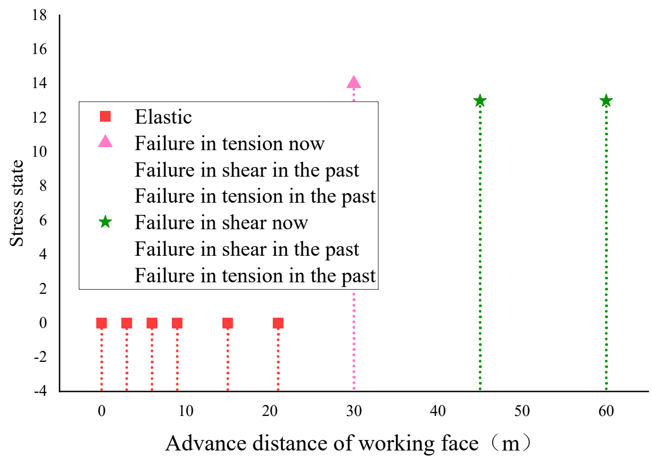

Figure 13. Evolution Characteristics of Stress State in Goaf on Non-Cutting Side

6. Conclusions

Mining models, evolution laws of three-dimensional principal stresses and rock mass fracture modes constitute the core teaching content of the course Mine Safety Engineering, which directly affects students' understanding of mine disaster mechanisms. Adopting a combined method of theoretical analysis and 3DEC distinct element numerical simulation, this study systematically investigates mining-induced stress evolution characteristics and rock mass failure mechanisms in the goaf under the N00 longwall mining method, and provides new technical approaches and teaching ideas for the experimental teaching reform of mine safety engineering. The main conclusions are drawn as follows:

(1) This study elaborates on the roadway layout of the N00 longwall mining method and the structural characteristics of the automatically formed roadway. The engineering principle and technical advantages of directional hydraulic roof cutting technology are emphatically discussed, offering theoretical support for students to understand the correlation between mining technology and mechanical responses of rock masses.

(2) Based on 3DEC numerical simulation tests, the dynamic evolution law of three-dimensional principal stresses at the monitoring point on the cutting side of the goaf is revealed. The results show that the magnitudes of three-dimensional principal stresses exhibit a nonlinear evolutionary characteristic of "increase–decrease–increase" during mining disturbance, accompanied by obvious deflection of principal stress orientations. This process visually

demonstrates the dynamic evolution of the mining-induced stress field and compensates for the deficiencies of traditional static mechanical analysis.

(3) The failure modes of rock masses at different positions in the goaf are clarified. The roof rock blocks on both sides of the goaf are dominated by tension-shear composite failure, while shear failure prevails in the central region. This conclusion helps students comprehend the differential occurrence mechanism of mine disasters and lays a foundation for learning prevention and control technologies for roof disasters, gas disasters, water inrush disasters and other hazards.

(4) The above results indicate that the 3DEC numerical simulation method can effectively overcome the limitations of conventional teaching methods. Its visualized and dynamic features help greatly improve students' cognition of complex mine disaster mechanisms. This method not only enriches experimental teaching approaches, but also provides an effective way for students to master analytical methods for engineering problems, which is of positive significance for cultivating innovative mining professionals.

7. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Educational Science Research Project of the University of Emergency Management: Research on the Reconstruction of Talents' Core Literacy and Learning Motivation against the Background of Digital Transformation (Grant No. JY2025B06)

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