

Research on the Bearing Structure Movement of Overburden Strata in Stope under Thick Sandstone Conditions and Its Energy Accumulation and Dissipation Evolution Characteristics

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Abstract: In response to the complex occurrence of coal bearing strata leading to severe overburden strata instability and mining pressure, especially the instability of thick sandstone roof causing strong dynamic pressure disasters, threatening operational safety, and causing surface damage. This article takes the fully mechanized coal mining face with thick sandstone conditions in the western mining area of Inner Mongolia as the research object, and uses a combination of physical model experiments and numerical simulation analysis to explore the movement characteristics and energy accumulation and dispersion evolution relationship of the overlying strata bearing structure in the mining area. The study found that the overlying strata in the mining area exhibit a progressive instability process from bottom to top, characterized by the "thick sandstone roof hanging-breaking-instability" during the working face mining. The deformation of the thick sandstone roof is not obvious before it breaks, and it quickly becomes unstable after reaching the bearing limit. It is necessary to strengthen prediction and technical treatment; The energy accumulation at the ends and middle of the exposed area before the rupture is significant, and the accumulation amount is positively correlated with the unstable dynamic load intensity. At the moment of rupture, the energy is released and converted into unstable kinetic energy, and at the same time, it reaccumulates at the exposed part of the overlying high-level thick sandstone roof. Under the same conditions, the unstable kinetic energy of the low position thick sandstone roof has a shorter transmission distance and smaller loss, resulting in more significant impact on the direct roof and support of the working face. The kinetic energy of the high position thick sandstone roof decays significantly, and the impact of strong dynamic pressure on disasters needs to be analyzed in conjunction with specific rock conditions and load transfer. This study reveals the laws of overlying rock movement and energy evolution in thick sandstone mining conditions, providing a scientific basis for the identification and treatment of strong dynamic pressure disasters in coal mining faces.

Keywords: Stope; Overburden strata movement; Strong dynamic pressure; Energy accumulation-dissipation evolution; Pre-splitting blasting for roof cutting

1. Introduction

For the mining conditions of extra-thick coal seams, the fully mechanized top coal caving longwall mining method has obvious advantages such as large mining thickness per pass, continuous and concentrated production, high resource recovery efficiency, low frequency of working face replacement, and low engineering cost input. It has realized high-efficiency mining of extra-thick coal seams and guaranteed national energy supply security. However, due to the complex occurrence conditions of coal measure strata, the strata behavior of overburden strata instability in the stope is particularly complex and severe. This seriously threatens the safety of

personnel and production equipment at the working face, and the evolution of mining-induced fractures in the overlying deep rock strata causes serious mining damage to the surface of the mining area.

Due to the complex geological occurrence conditions, research on the mining-induced instability evolution of stope overburden strata and its pressure impact under different coal seam mining conditions and rock strata occurrence conditions is particularly urgent. Ju J., Li H., Yasitli N., et al. used physical simulation and numerical simulation methods to analyze the fracture laws of overburden strata and stope stress distribution under different mining height conditions, and analyzed the dynamic pressure impact mechanism of key stratum fracture instability on the underlying bearing strata based on strata pressure theory[1~3]. Shen W., Kevin J., Wang F., et al. studied the overburden strata movement laws of fully mechanized top coal caving faces with large mining heights in extra-thick coal seams, revealing the mechanical manifestation characteristics of hard roofs in caving faces and how the movement state of surrounding rock affects the working condition and bearing characteristics of supports[4~6]. Yu B., Zhang H., et al. conducted actual measurement analyzes on the distribution characteristics of overburden strata fracture frequency in horizontal and vertical directions under hard roof mining conditions of extra-thick coal seams through the application of borehole digital imaging and microseismic monitoring technologies[7,8]. Yu B., Zhu W., Liu C., et al. conducted research on strata pressure and strata control of stope overburden strata structures under extra-thick coal seam mining conditions in the Large mining area, proposed the concept of "large space stope," and established the "masonry beam" structural models of "vertical O-X" fracture for near-field key strata and "horizontal O-X" fracture for far-field key strata, playing an important role in guiding the safe mining of extra-thick coal seams in the Datong mining area [9~11].

Since the early 20th century, experts and scholars have begun to introduce energy dissipation theory into the research process of underground rock engineering to analyze the energy accumulation and instability release during the bearing and failure process of coal and rock media [12~21]. Li X., Gao W., Xie H., Xia C., et al. conducted rock mechanics experiments under different mechanical loading states in the laboratory to analyze the laws of energy accumulation and dissipation evolution during rock fracture instability and the transformation laws of external loading work [22~27]. The energy evolution of rock (mass) has been widely studied in aspects such as coal and rock medium rupture, coal and gas outburst, rockburst, and pressure bumps. regarding the energy evolution analysis of mining-induced instability of thick rock roofs in stopes, Tan Y., Song X., et al. analyzed the phenomenon of strong strata pressure manifestations in working faces with thick rock roofs through investigation and actual measurement, revealing that the thick rock layer itself and the underlying bearing coal and rock mass accumulate a large amount of elastic energy, and the mining-induced instability of the thick rock roof poses hidden dangers of inducing rockbursts and air blasts in the working face[25,26]. Wang P. et al. through analyzing the dynamic load manifestation characteristics of thick hard roof fracture, believed that the fracture of thick rock layers leads to the instantaneous transfer of in-situ stress, and its instability fracture and in-situ stress transfer release energy in the form of vibration, forming microseisms or mine tremors[27].

In summary, fruitful results have been achieved in research on the instability evolution of stope overburden strata bearing structures and mining disasters, providing strong scientific and technological guarantees for the safe and efficient mining of coal resources. However, the problem of disasters caused by mining-induced instability of thick rock roofs in stopes remains prominent. The conditions of thick rock roofs make the strong dynamic pressure manifestation of stope overburden strata structural movement particularly complex. There exists a phenomenon where the fracture movement of lower-strength thick rock layers causes linkage instability of the underlying harder-strength thick rock layers. The instability of thick sandstone roofs in stopes releases accumulated energy in the form of vibration, causing particularly severe strong dynamic pressure impacts on the stope surrounding rock and working face support equipment. Identifying the key strata responsible for the danger of strong dynamic load manifestation in stope overburden strata is

crucial. This provides important scientific research support for the evaluation of the impact of strong dynamic loads on hydraulic supports in working faces and their precise governance. This paper takes a fully mechanized top coal caving face under thick sandstone conditions in a coal mine in the western Inner Mongolia mining area as the research object. It carries out physical model experimental analysis of the movement characteristics of the overburden strata bearing structure in the stope under thick sandstone conditions, as well as simulation analysis of the energy accumulation and dissipation evolution characteristics. This reveals the movement characteristics of the overburden strata bearing structure and the energy accumulation and dissipation evolution relationship.

2. Engineering Overview of Coal Mining Face under Thick Sandstone Conditions

The 304 fully mechanized top coal caving face in a coal mine in the western Inner Mongolia mining area has a strike length of 2100 m and a dip length of 240 m. The average burial depth of the main minable coal seam is 520 m. The average recoverable coal thickness is nearly 17 m. The coal thickness is relatively stable and contains 4 to 6 layers of gangue (partings), which are mudstone and sandy mudstone. The coal seam dip angle is $0\sim 6^\circ$, with an average of 2° .

Serial Number	Stratum Name	Deep ground/m	Layer thickness/m	Columnar	Layering characteristics	Serial Number	Stratum Name	Deep ground/m	Layer thickness/m	Columnar	Layering characteristics
1	Medium-grained sandstone	214.7	14.3		Layering is obvious	16	Sandy mudstone	457.2	12.2		More layers
2	Sandy mudstone	227.7	13.5		More layers	17	Fine-grained sandstone	465.3	8.1		Layering is not obvious
3	Medium-grained sandstone	245.3	17.6		Layering is obvious	18	Sandy mudstone	471.7	6.4		More layers
4	Sandy mudstone	259.9	14.6		More layers	19	Coal No. 4	473.3	1.6		More layers
5	Fine-grained sandstone	273.1	13.2		Layering is not obvious	20	Sandy mudstone	480.4	7.1		More layers
6	Sandy mudstone	277.6	4.5		More layers	21	Sandy mudstone	483.0	2.6		More layers
7	Medium-grained sandstone	292.9	15.3		Layering is obvious	22	Fine-grained sandstone	498.8	15.8		Layering is not obvious
8	Sandy mudstone	304.3	11.4		More layers	23	Mudstone	503.3	4.5		More layers
9	Fine-grained sandstone	313.0	8.7		Layering is not obvious	24	Coal No. 6	520.1	16.8		More layers
10	Sandy mudstone	331.6	18.6		More layers	25	Mudstone	525.7	5.6		More layers
11	Medium-grained sandstone	356.0	24.4		Layering is obvious	26	Medium-grained sandstone	530.7	5.0		Layering is obvious
12	Sandy mudstone	362.0	6.0		More layers	27	Sandy mudstone	533.2	2.5		More layers
13	Fine-grained sandstone	393.5	31.6		Layering is not obvious	28	Medium-grained sandstone	540.2	7.0		Layering is obvious
14	Sandy mudstone	421.6	28.1		More layers	29	Sandy mudstone	545.2	5.0		More layers
15	Fine-grained sandstone	445.0	23.4		Layering is not obvious	30	Fine-grained sandstone	557.6	12.4		Layering is not obvious

Fig.1 Column chart of coal and rock layer in no.304 working face

According to the collected coal mine geological report, as shown in Figure 1, the immediate roof and immediate floor are 4.5 m thick and 5.6 m thick mudstone layers, respectively. The horizontal bedding is obvious, and the strength of the rock strata medium is relatively low. However, a 15.8 m thick fine sandstone layer occurs above the immediate roof. Additionally, thick fine sandstone layers with thicknesses of 8.1 m, 23.4 m, 31.6 m, 8.7 m, and 13.2 m occur at horizons 55 m, 75 m, 116 m, 207 m, and 247 m above the coal seam, respectively. The medium of these fine sandstone layers is relatively dense, the horizontal bedding distribution is not obvious, and the strength is relatively high. In other horizons, sandy mudstone layers and medium-grained sandstone layers primarily occur. The sandy mudstone layer medium has obvious horizontal bedding and argillaceous cementation. The medium-grained sandstone layer medium shows obvious development of cross-bedding, with local intercalations of loose conglomerate. The strengths of both the sandy mudstone layers and medium-grained sandstone layers are generally low.

According to on-site investigation and analysis, the strong strata pressure manifestation of the thick sandstone roof is prominent, posing a serious threat to the safe and efficient mining of the coal mine. How to scientifically evaluate the movement of the thick sandstone roof structure in the stope,

analyze the strong strata pressure impact of instability based on the bearing structure and its energy accumulation, and then carry out targeted roof cutting strata pressure control, is particularly important for ensuring safe and efficient coal mining.

3. Physical Model Experiment Analysis of Movement Characteristics of Stope Overburden Strata Bearing Structure under Thick Sandstone Conditions

Physical model experiments on the movement evolution of the stope overburden strata bearing structure under thick sandstone conditions were carried out to analyze the fracture evolution and fracture block instability of stope overburden strata movement during the fully mechanized top coal caving mining of thick coal seams, revealing the movement characteristics of the bearing structure.

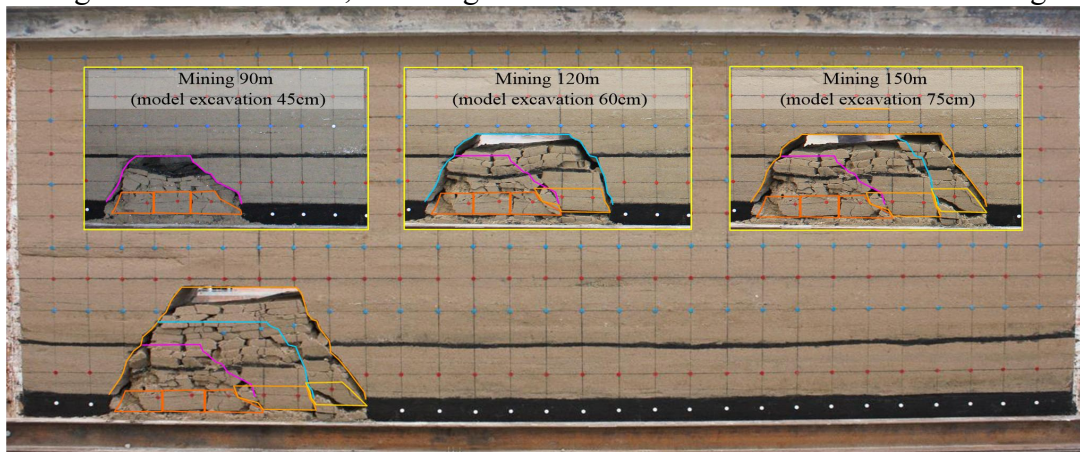


Fig.2 Overburden strata movement during 90~150 m mining (model excavation 45~75 cm)

When the coal seam mining distance reaches 70~90 m, as shown in Fig.2, the 15.8 m thick fine sandstone main roof (basic roof) and its overlying strata begin to gradually show separation cracks. When the coal seam is mined to a distance of 90 m, the fine sandstone main roof and its overlying strata break. The broken blocks exhibit the characteristic of hinged rotation instability. During the mining-induced instability evolution of the 15.8 m thick fine sandstone main roof, the hanging span of the thick fine sandstone roof before mining-induced instability is relatively large, and at the moment of mining-induced instability, it breaks and destabilizes together with its overlying weak strata. When the coal seam is mined to a distance of 150 m, the fine sandstone main roof undergoes periodic fracture instability again. Judging from the dimensions of the two periodic fractures, the instability span of the fine sandstone main roof is relatively large, and the broken blocks exhibit hinged rotation instability characteristics afterward.

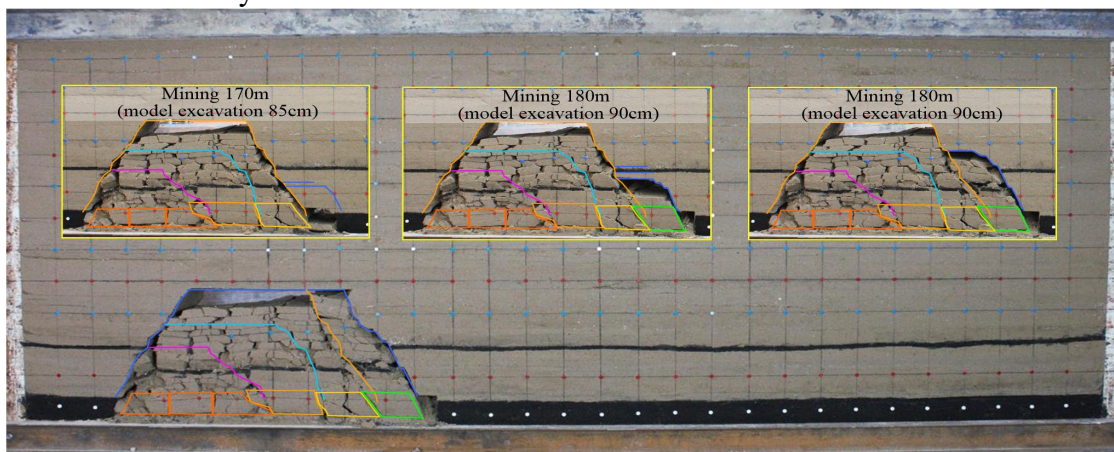


Fig.3 Overburden strata movement during 170~180 m mining (model excavation 85~90 cm)

As shown in Fig.3 and 4, when the coal seam mining distance reaches 170~200 m, the 23.4 m thick fine sandstone shows separation cracks, followed by fracture instability of the thick fine sandstone roof at this horizon. The overlying sandy mudstone, medium-grained sandstone, and other strata at this horizon subsequently undergo mining-induced deformation and instability. At this time, the fracture trace of the stope overlying strata presents an approximate positive trapezoidal spatial evolution characteristic of 55~70°.

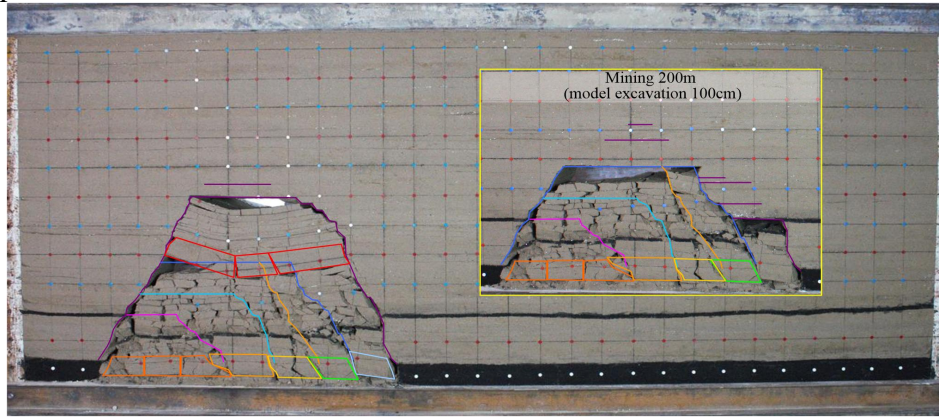


Fig.4 Overburden strata movement during 200 m mining (model excavation 100 cm)

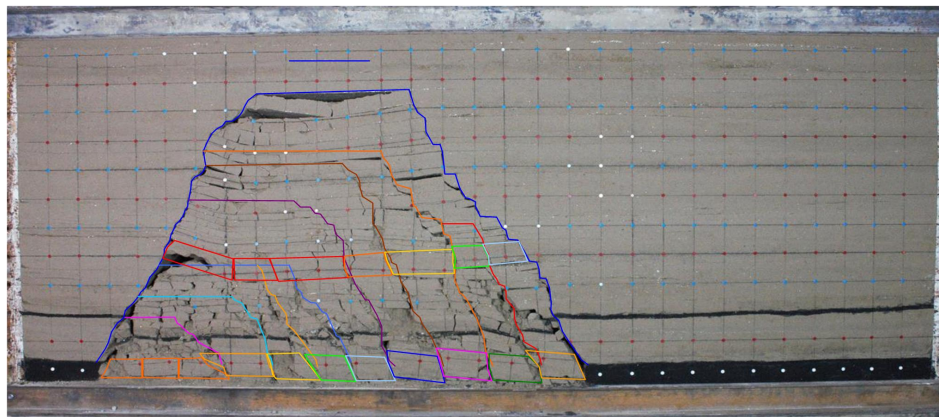


Fig.5 Overburden strata movement during 320 m mining (model excavation 160 cm)

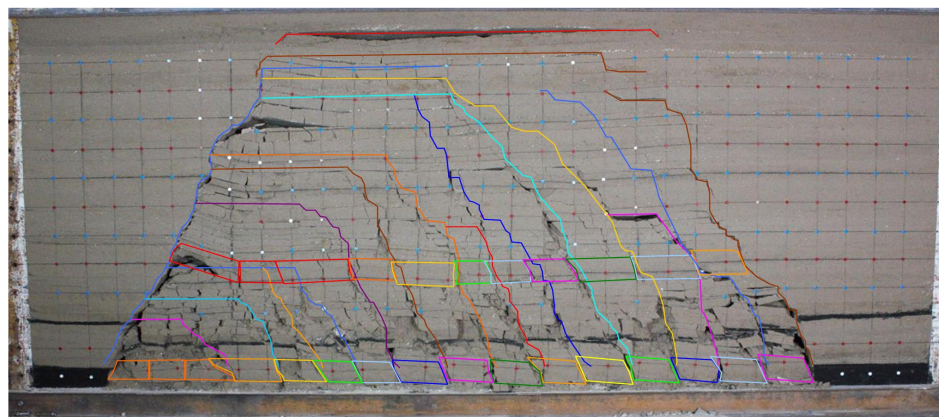


Fig.6 Overburden strata movement during 470 m mining (model excavation 235 cm)

As shown in Figures 5 and 6, the current mining thickness of the thick coal seam reaches 16.8 m, leading to a large development height of the mining-induced fracture zone in the overlying strata. The physical model experiment begins to show bending separation at the horizon 220 m away from the coal seam, and the rock strata in the mining-induced separation zone no longer undergo fracture through-crack evolution. Due to the large mining thickness of the coal seam, the mining-induced fractures of the stope overburden strata continue to develop and evolve towards the deep

overburden strata. Within the range of mining-induced fractures, the stope overburden strata takes the thick fine sandstone at each horizon as the bearing boundary, forming a "composite mining bearing structure" composed of the thick fine sandstone roof and the overlying weak strata. This structure undergoes mining-induced instability fracture evolution from bottom to top, and the mining-induced fracture trace presents an approximate "positive trapezoidal" spatial form of about 70°.

In addition, the physical model experiment results combined with on-site strata pressure safety impact analysis suggest that the instability of the low-position thick fine sandstone roof above the working face has a relatively strong dynamic pressure impact on the working face roof and hydraulic supports, while the instability of the high-position thick fine sandstone roof has a relatively weak dynamic pressure impact on the working face roof and hydraulic supports. The strata pressure manifestation characteristics of the thick sandstone roof before mining-induced instability are not obvious and difficult to detect. At the moment of mining-induced fracture instability, the instability evolution of the thick sandstone roof and its overlying weak strata is rapid, and the scale of mining-induced instability is relatively large.

4. Simulation Analysis of Energy Accumulation and Dissipation Evolution Characteristics of Stope Overburden Strata Bearing Structure Movement under Thick Sandstone Conditions

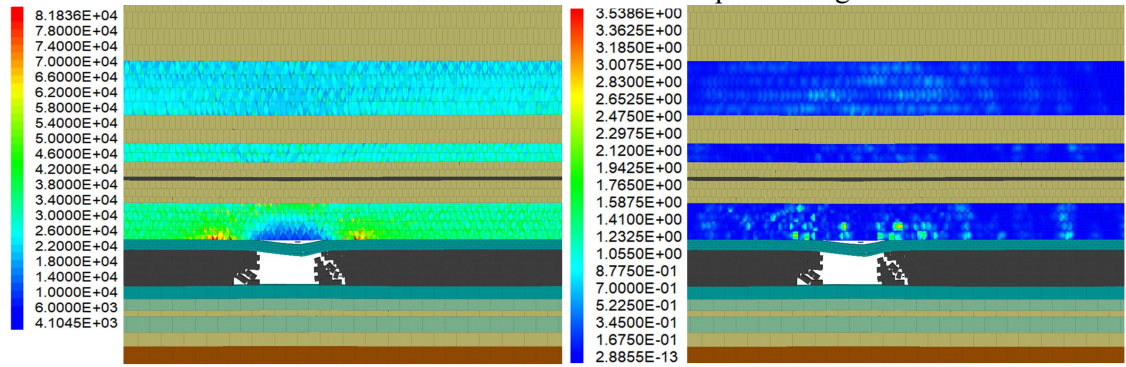
4.1 Numerical Modeling

Based on the research background of the 304 fully mechanized top coal caving face, the DEM numerical simulation was used to carry out the simulation analysis of the energy accumulation and dissipation evolution characteristics of the stope overburden strata bearing structure movement under thick sandstone conditions. From the aspects of mining-induced energy accumulation and instability kinetic energy manifestation, the potential energy accumulation and instability kinetic energy manifestation of the stope overburden strata bearing structure movement under thick sandstone conditions were analyzed. This further reveals the energy accumulation and dissipation evolution relationship of the stope overburden strata bearing structure movement under thick sandstone conditions, providing a basis for the governance of strong dynamic pressure disasters in the working face. Using the FISH language embedded in the numerical simulation software, programming for model unit energy calculation was performed. By traversing the model grid cells, cloud maps of mining-induced accumulated energy and instability manifestation kinetic energy distribution were generated to facilitate the simulation analysis of the energy field evolution.

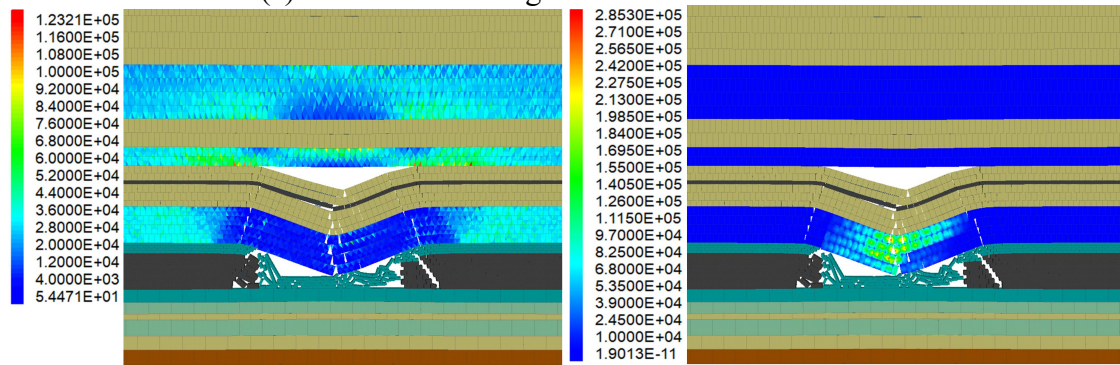
4.2 Analysis of Simulation Results

The potential energy accumulation and instability kinetic energy manifestation of the stope overburden strata bearing structure movement under thick sandstone conditions are analyzed from the aspects of mining-induced energy accumulation and instability kinetic energy manifestation, as shown in Fig.7~8.

As can be seen from Fig.7, since the mining of the working face open-off cut, the top coal and the immediate mudstone roof collapse and destabilize. A clear mining-induced energy accumulation evolution is formed in the 15.8 m thick fine sandstone layer roof above the immediate roof. The peak mining-induced accumulated energy density formed at the end of the hanging area of the thick fine sandstone roof reaches 125.2 kJ/m³, while the peak kinetic energy density of the roof manifestation in the hanging area is only 0.8 J/m³. The mining-induced kinetic energy manifestation of the thick sandstone roof is not obvious, indicating again that the strata pressure manifestation of the fine sandstone thick roof bearing structure before mining-induced instability is difficult to detect.



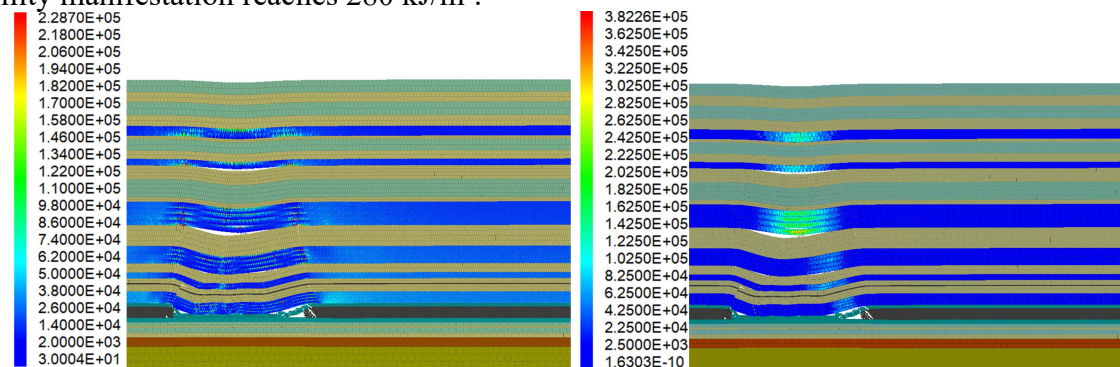
(i) Mining potential energy accumulation (ii) Unstable kinetic energy manifestation
(a) When the working face is mined at 45~50 m



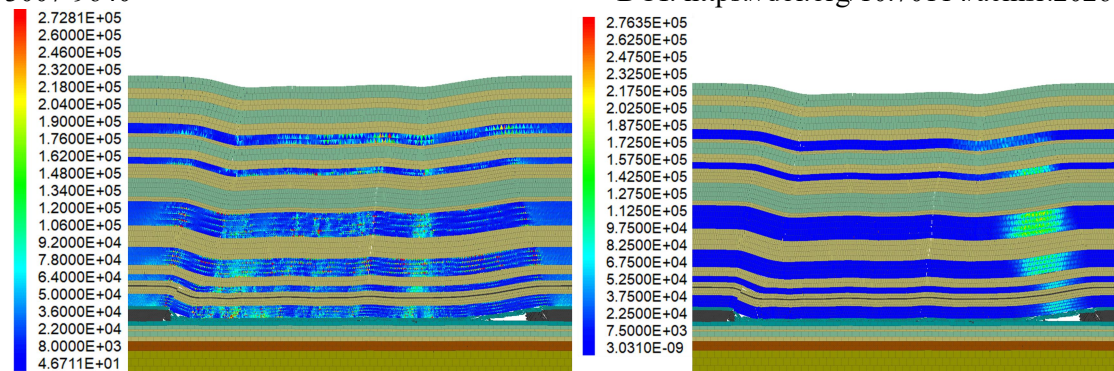
(i) Mining potential energy accumulation (ii) Unstable kinetic energy manifestation
(a) When the working face is mined at 80~85 m

Fig.7 The energy field evolution of overburden strata movement in stope under thick sandstone roof condition (working face mining at 45~85 m)

As can be seen from Fig.8 (a), when the overlying 31.6 m thick fine sandstone layer roof reaches its bearing limit, the kinetic energy density of the mining-induced instability manifestation reaches 382 kJ/m^3 . The 31.6 m thick fine sandstone layer roof above it presents energy accumulation, at which point the mining-induced accumulated energy density reaches 228 kJ/m^3 , and the accumulated energy density at the end of its hanging area reaches 100 kJ/m^3 . During the advancement of the working face, the broken hinged blocks above the working face are in an unstable bearing state, and their hinged instability leads to the re-manifestation of mining-induced instability kinetic energy. As shown in Fig.8 (b), the stope overburden strata presents periodic mining-induced instability evolution, and the kinetic energy density of the mining-induced instability manifestation reaches 280 kJ/m^3 .



(i) Mining potential energy accumulation (ii) Unstable kinetic energy manifestation
(a) When the working face is mined at 200~215 m



(i) Mining potential energy accumulation (ii) Unstable kinetic energy manifestation
(b) When the working face is mined at 495~500 m

Fig.8 The energy field evolution of overburden strata movement in stope under thick sandstone roof condition (working face mining at 200~500 m)

Analysis of the potential energy accumulation and instability kinetic energy manifestation of the stope overburden strata bearing structure movement under thick sandstone conditions concludes: Before mining-induced fracture instability, the thick sandstone roof shows obvious mining-induced energy accumulation at the ends and middle of the hanging area. The greater the energy accumulation, the more severe its mining-induced bearing stress state, and the stronger the dynamic load manifested at the moment of instability. At the moment of mining-induced fracture instability of the thick sandstone roof, the accumulated energy is released and converted into instability kinetic energy together with the work done by the overlying mining-induced transfer load.

5. Technical Scheme Design of Roof Cutting for Working Face under Thick Sandstone Conditions and Its Engineering Application Practice

5.1 Roof Cutting Blasting Design for Thick Sandstone Roof

Combining the consideration of the cementation of the overlying strata of the coal seam on-site, it is believed that the rock strength and cementation of the coal line horizon are relatively weakest, which is conducive to the cutting and falling of mining-induced separation after roof cutting. To ensure an effective roof cutting effect, the design proposes to implement pre-splitting blasting jointly on the 15.8 m thick fine sandstone layer main roof and its overlying 2.6 m thick sandy mudstone layer and 7.1 m thick sandy mudstone layer. The designed blasting charge length is 26 m. Sealing is performed at the top coal caving height of 12.3 m and the 4.5 m mudstone immediate roof part. The designed sealing length is 17 m. The designed total length of the blast hole is 43 m. The blast holes are arranged at the working face open-off cut 500 mm from the rear solid coal side rib, and roof cutting blasting boreholes are arranged in the return airway within 50 m from the open-off cut mining coal wall and 500 mm from the rib on the coal pillar side. The borehole diameter is $\Phi 70 \text{ mm} \times 43000 \text{ mm}$. The borehole spacing is determined to be 800 mm through perforation blasting tests.

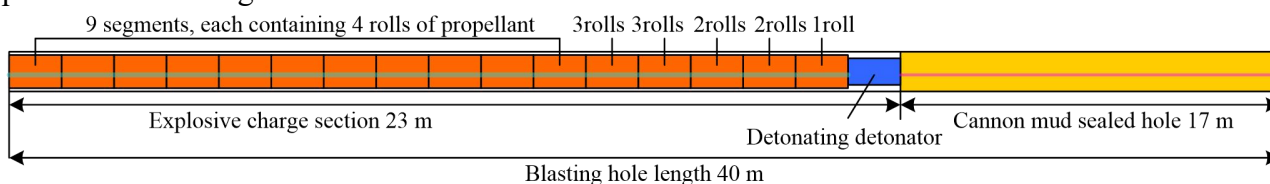


Fig.9 Structure diagram of blast hole charge for pre splitting blasting and top cutting of working face

Bidirectional energy-cumulative blasting technology is adopted. The special energy-cumulative tube has a long axis outer diameter of 49 mm, a short axis outer diameter of 41 mm, and a tube

length of 1500 mm. The explosive uses secondary coal mine emulsion explosive with a specification of $\Phi 35 \times 300$ mm/roll. Each borehole is loaded with 17 energy-cumulative tubes. Starting from the bottom of the hole, a charging structure of "4+4+4+4+4+4+4+4+4+4+4+3+3+2+2+1" is adopted, as shown in Fig.9. The blast hole collar is sealed with special stemming, and the blasting network connection uses a detonating cord series connection method.

5.2 Microseismic Feedback of Coal and Rock Strata

The microseismic monitoring results of the coal and rock strata in the working face indicate: During the current period from the working face open-off cut coal wall to 65 m of mining, the microseismic events caused by mining-induced damage to the stope overburden strata are mainly concentrated in the coal and rock strata from the floor of the #4 coal seam to the floor of the #6 coal seam. This horizon is mainly the 15.8 m thick fine sandstone roof. Moreover, there is a significant surge in microseismic events at the 26~29 m and 57~59 m mining positions of the working face. This once again explains that the overlying 15.8 m thick fine sandstone roof of the working face underwent two mining-induced fracture instabilities at the mining positions of 26~29 m and 57~59 m. The 15.8 m thick fine sandstone layer main roof was effectively cut off, changing the large hanging roof structure and its resulting strong dynamic pressure impact in the initial mining stage, ensuring the safe mining of the working face.

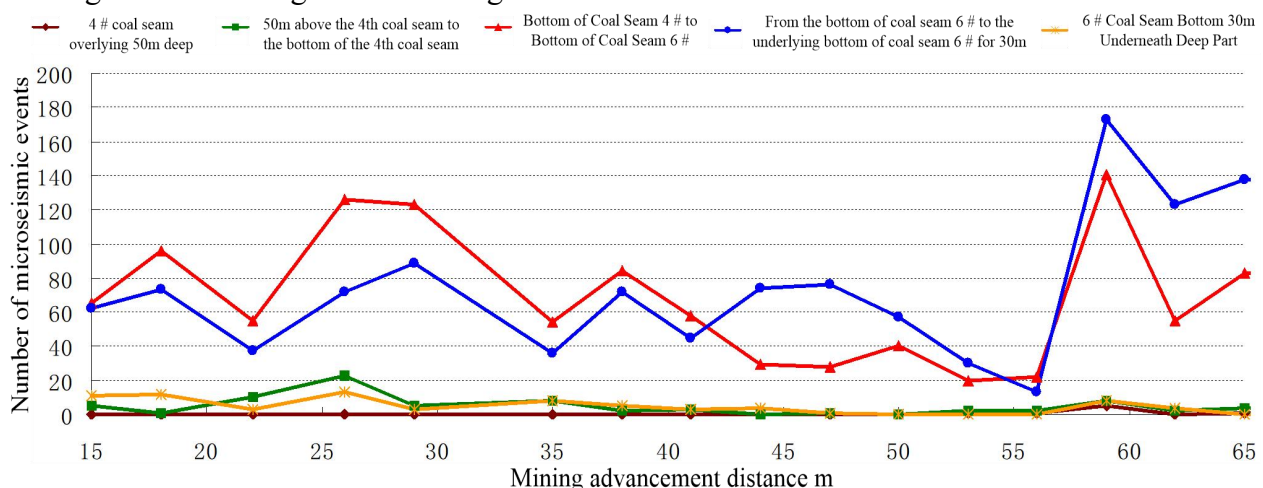


Fig.10 Microseismic Monitoring of middling coal Strata in Mining Process of Working Face

6. Conclusion

(1) With the continuous mining of the working face, the stope overburden strata presents a bottom-up stepwise recursive mining-induced instability evolution process of "stope thick sandstone roof hanging – thick sandstone roof fracture instability – overlying thick sandstone roof hanging – overlying thick sandstone roof fracture instability."

(2) The mining-induced deformation manifestation of the thick sandstone roof before fracture instability is not obvious and is difficult to detect. Once the bearing limit is reached, it will rapidly undergo fracture instability evolution. On-site, it is necessary to attach importance to the prediction and technical treatment of the impact of mining-induced instability of the thick sandstone roof to avoid strong weighting affecting normal safe production.

(3) Before the mining-induced fracture instability of the thick sandstone roof, obvious mining-induced energy accumulation appears at the ends and middle of the hanging area. The greater the energy accumulation, the more severe the bearing stress, and correspondingly, the stronger the dynamic load manifested at the moment of instability. At the moment of mining-induced fracture instability of the thick sandstone roof, the accumulated energy is released and converted into instability kinetic energy together with the work done by the overlying

mining-induced transfer load, while mining-induced energy re-accumulates in the hanging bearing parts of the overlying adjacent high-position thick sandstone roof.

(4) The dynamic load impact of the mining-induced instability kinetic energy of the high-level thick sandstone roof on the working face immediate roof is relatively weaker than that of the low-level thick sandstone roof. Under the same conditions, the mining-induced fracture instability kinetic energy of the stope low-position thick sandstone roof is closer to the working face roof, and the energy transmission loss is small, so the impact dynamic load effect on the working face immediate roof and supports is obvious. The mining-induced instability kinetic energy of the high-level thick sandstone roof attenuates increasingly due to the longer propagation distance. Whether the thick sandstone roof condition of the stope forms a strong dynamic pressure disaster impact on the working face requires analysis based on the specific rock strata conditions of the stope and the load transmission situation.

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References

- [1] Ju J., Xu J. Structural characteristics of key strata and strata behavior of fully mechanized longwall face with 7.0m height chocks[J]. International Journal of Rock Mechanics and Mining Sciences, 2013,58(02):46-54.
- [2] Li H., Jiang D., Li D. Analysis of ground pressure and roof movement in fully-mechanized top-coal caving with large mining height in ultra-thick seam[J]. Journal of China Coal Society, 2014,39(10):1956-1960.
- [3] Yasitli N., Unver B. 3D numerical modeling of longwall mining with top-coal caving[J]. International Journal of Rock Mechanics and Mining Sciences,2005,42(02):219-35.
- [4] Shen W., Bai J., Wang X., et al. Response and control technology for entry loaded by mining abutment stress of a thick hard roof [J].International Journal of Rock Mechanics and Mining Sciences, 2016,90:26-34.
- [5] Kevin J., John S. Case study and design of steel set support for aged belt entry rehabilitation [J]. International Journal of Mining Science and Technology,2018,28:101-106.
- [6] Wang F., Duan C., Tu S., et al. Hydraulic support crushed mechanism for the shallow seam mining face under the roadway pillars of room mining goaf [J]. International Journal of Mining Science and Technology,2017,27:853-860.
- [7] Yu B., Zhao J., Xiao H. Case study on overburden fracturing during longwall top coal caving using microseismic monitoring[J].Rock Mechanics and Rock Engineering,2017,50: 507-511.
- [8] Zhang H., Zhu Z., Huo L., et al. Overburden failure height of superhigh seam by fully mechanized caving method [J]. Journal of China Coal Society, 2014, 39(05):816-821.
- [9] Yu B. Research on the mechanism of strong mining pressure manifestation and roof control in the fully mechanized mining of thick coal seams in Datong mining area [D]. Xuzhou: China University of Mining and Technology, 2014.
- [10] Yu B. Evolution of overlying fractured roof structures in multiple coal seams and their impact on lower coal seam mining [J]. Coal Journal, 2015, 40 (02): 261-266.
- [11] Gao R. Research on the Mechanism of Mineral Pressure and Surface Fracturing Control in the Fracture and Instability of Remote Hard Rock Layers [D]. Xuzhou: China University of Mining and Technology, 2018.

- [12] Horn H., Nemat N. Compression-induced microcrack growth in brittle solids: axial splitting and shear failure [J]. *Journal of Geophysical Research*, 1985, 90: 3105-3125.
- [13] Hamdi P., Stead D., Elmo D. Characterizing the influence of stress-induced microcracks on the laboratory strength and fracture development in brittle rocks using a finite-discrete element method-micro discrete fracture network FDEM- μ DFN approach[J]. *Journal of Rock Mechanics and Geotechnical Engineering*, 2015, 07(06): 609-625.
- [14] Deng Q., Zhang P. Research on the geometry of shear fracture zones[J]. *Journal of Geophysical Research*, 1984, 89: 5699-5710.
- [15] Scholz C. The mechanics of earthquakes and faulting [M]. London: Cambridge University Press, 1990.
- [16] Martino J., Chandler N. Excavation-induced damage studies at the underground research laboratory [J]. *International Journal of Rock Mechanics and Mining Science*, 2004, 41(08): 1413-1426.
- [17] Deshpande V., Evans A. Inelastic deformation and energy dissipation in ceramics: a mechanism-based constitutive model[J]. *Journal of the Mechanics and Physics of Solids*, 2008, 56(10): 3077-3100.
- [18] Li X., Zhou Z., Lok T., et al. Innovative testing technique of rock subjected to coupled static and dynamic loads [J]. *International Journal of Rock Mechanics & Mining Sciences*, 2008, 45(05): 739-748.
- [19] Li X., Zhou Z., Zhao F., et al. Mechanical properties of rock under coupled static-dynamic loads [J]. *Journal of Rock Mechanics & Geotechnical Engineering*, 2009, 01(01): 41-47.
- [20] Cao W., Li X., Tao M., et al. Vibrations induced by high initial stress release during underground excavations [J]. *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, 2016, 53: 78-95.
- [21] Li X., Gu D. Theoretical exploration of energy dissipation of rocks under different loading wave conditions [J]. *Explosion and Shock*, 1994, 14 (02): 129-139.
- [22] Gao W., Liu Y. Energy dissipation of rock damage under impact load [J]. *Journal of Rock Mechanics and Engineering*, 2003, 22 (11): 1777-1780.
- [23] Xie H., Peng R., Ju Y. Energy dissipation analysis during rock deformation and failure process [J]. *Journal of Rock Mechanics and Engineering*, 2004, 23 (21): 3565-3570.
- [24] Xia C., Xie H., Ju Y., et al. Experimental study on energy dissipation of porous rocks under impact load [J]. *Engineering Mechanics*, 2006, 23 (09): 1-5.
- [25] Tan Y., Zhang M., Xu Q., et al. Research on the Mechanism and Monitoring Warning of Hard Top Plate Impact Ground Pressure [J]. *Coal Science and Technology*, 2019, 47 (01): 166-172.
- [26] Song X., Lian Q., Xing P., et al. Research on the Air Shock Disaster of Large Area Collapse of the Top Plate in goaf [J]. *Coal Science and Technology*, 2009, 37 (04): 1-4.
- [27] Wang P., Jiang F., Feng J., et al. Discussion on the relationship between high-level thick and hard roof fractures and mine earthquake prediction [J]. *Journal of Geotechnical Engineering*, 2011, 33 (04): 618-623.