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Structural model of hard overburden shell in thick coal seam and its application

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Taking the mining of extra-thick coal seam of Carboniferous hard overburden in tongxin coal mine of datong mining area as the engineering background, the movement characteristics of hard overburden in fully-mechanized caving mining of 3–5 # extra-thick coal seam are analyzed based on the key stratum theory. Based on the elastic plate theory, the mechanical model and mathematical model of the cylindrical shell structure of hard overburden in large space stope are established, and the ultimate span of the cylindrical shell structure is determined and applied in 8105 working face.The results show that the limit span of sub-key stratum II in 8105 working face is 65.11 m, and the limit span of main key stratum is 222.77 m. The calculation results are basically consistent with the actual mine pressure behavior. The mechanism of special mine pressure phenomena such as large and small periodic weighting, large mining influence range and easy impact load in the mining process of 8105 working face is revealed, which provides a theoretical basis for mine pressure control in the mining face of Carboniferous hard overburden and extra-thick coal seam in Datong mining area.

Keywords Hard roof, Extra-thick coal seam, Cylindrical shell structure, Mechanical model

The structural characteristics and movement forms of the overlying strata in the stope have a significant impact on the mine pressure behavior in the working face, the end of the working face and the empty roadway. Due to the different lithologies, thicknesses, horizon relationships and structures of the overlying strata, there are various movement laws in the overlying strata. The structural form of the roof determines the movement characteristics of the roof and is also a key factor in determining the method of roof control. The failure state and movement characteristics of overlying strata determine the degree of mine pressure in coal mining faces and are also important inducing factors of dynamic disasters such as mine earthquakes and rock bursts[1–3]. A variety of hypotheses and theories such as pressure arch hypothesis[4], hinged rock block hypothesis[5], natural equilibrium arch hypothesis[6], cantilever beam hypothesis[7], pre-existing fracture hypothesis and key stratum theory[8] are proposed for the movement structure of overlying strata in the stope, which provides a theoretical basis for the study of the formation and instability of mining overburden structure. Based on the theory of key strata, Xu Xuefeng et al.[9] divided the overlying strata structure of a coal mine and analyzed the fracture law of superthick overlying strata by using microseismic monitoring technology. The results show that the overlying strata can be divided into different levels of key stratum structure according to the lithology and thickness. The 'O-X' type fracture structure formed by the initial fracture of these structures is divided into primary and secondary structures. Zhao Yanhai[10] studied the far-field arch shell structure existing outside the fracture arch of overlying strata in a stope by means of theoretical analysis and numerical simulation. According to the mechanical criterion of vertical pressure release and the arching index of compressive stress, the loading and unloading state of far-field surrounding rock and the evolution characteristics of the arching effect under the influence of principal stress axis deflection are characterized. Based on theoretical calculations, microseismic monitoring, stress on-line monitoring and other methods, Lu Yangbo[11] studied the change in the spatial structure of different overburden strata and its influence on mine pressure behavior under different goaf boundary conditions during the mining process of the working face and obtained the characteristics of strong mine pressure behavior and the distribution law of dangerous areas under different overburden strata spatial structures. By studying the spatial structure characteristics of overlying strata composed of 'residual coal pillar-key stratum in goaf', Wang Gao 'ang[12] established a stress distribution estimation model of residual coal pillars in goafs and a limit span calculation mechanical model of inclined key strata under an asymmetric overlying strata spatial structure. Han Hongkai et al.[13] established a stress field prediction model based on the plate-beam structure of the key strata of mining overburden and proposed a plane distribution prediction method for mining stress and stope abutment

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pressure under different key strata. The measured results of the mining stress and the law of mine pressure in the Tingnan and Haizi coal mines were verified. Zhang Junwen[14] used a single-layer curved thin plate as an example to establish a mechanical model of the plate in different mining stages and revealed the bending energy release characteristics of the plate structure in different mining stages. Based on the theory of structural control, prevention and control measures for rock bursts during initial and final mining to reduce the collapse span of thick and hard strata were proposed. Ma Qihua[15] suggested that there are two spatial structures in the overlying strata of the stope: the large spatial structure of plate-shell evolution in the overlying strata of the whole goaf and the small spatial structure of hinged rock plate semiarch evolution around the goaf. The formation process of the 'O'-type spatial structure of the overlying strata is essentially the evolution process of the two spatial structures. Through numerical simulations, theoretical calculations and field industrial tests, Du F et al.[16] comprehensively analyzed the structural characteristics and support adaptability of the overburden layer in a working face. It is concluded that the stress arch bearing structure can be formed above the segmented coal pillar during cooperative coal mining, which is controlled by the key strata. The stress arch bearing structure is formed in the overburden above the section coal pillar, which provides protection for the lower mining area. Jiangguo Zhang J et al.[17] studied the fracture and structural distribution evolution characteristics of overlying strata in deep large mining height working faces. According to the deformation characteristics of the overlying strata, the failure modes of the overlying strata are divided into two categories: (I) nonseparation type and (II) separation type. Xinfeng Wang X et al.[18] studied the temporal and spatial evolution law and mechanism of instability and failure of deep high-stress overburden rock. Ning J et al.[19] studied the structural characteristics of the overlying strata above the goaf of a shallow coal seam and concluded that the height of the water flow in the water-conducting fractured zone is proportional to the burial depth of the coal seam after coal seam mining. Shiguo G[20] and other steeply inclined thick coal seam horizontal sublevel mining overburden structure characteristics were studied. It is concluded that after the roof overburden is broken, a hinged bearing structure is formed under the support of the sliding force of the fault block and the floating gangue in the goaf. Xiangyang Z[21] studied the structural evolution and movement characteristics of a hard roof in the process of thick coal seam mining and concluded that in the process of thick coal seam mining with a hard roof, the settlement curve of the low rock layer showed a step-like fluctuation slope, and the settlement curve of the high rock layer changed from a 'V' type distribution to a parabola under full mining of the coal seam. Wang Y et al.[22] studied the overburden structure of an island working face in an extrathick coal seam and established a mechanical model of the mining stress and overburden stress arch in the working face. Zhiqiang H et al.[23] studied the fracture characteristics and mining stress behavior of hard roofs. With respect to three kinds of periodic weighting phenomena, three kinds of hard roof fracturing models are proposed based on cantilever beam–masonry beam composite structures. Based on the theory of plate and shell and the theory of fracture mechanics, Liu Gang et al.[24] established a fracture mechanics model of coal seam floor with concealed collapse column water inrush, and revealed the fracture mechanism of coal seam floor when collapse column water inrush. Zhai Huichao[25] established a mechanical model of plate and shell structure by using elastic theory, and analyzed the roof stability of goaf. Ding Ziwei et al.[26] established the mechanical model of the thin plate in the empty top area based on the bending example of the rectangular thin plate based on the theory of plate shell and elasticity, and revealed the different mechanical mechanisms. References[27,28] revealed the evolution of hard roof instability and the evolution of energy accumulation and dissipation during the instability process.The mechanical model of overburden structure mentioned in the above literature is mostly theoretical analysis under two-dimensional conditions. For the research on the movement and instability characteristics of overlying hard rock strata in the mining of extra-thick coal seam working face, the spatial scale of working face along strike and tendency should be fully considered, and the mechanical model of three-dimensional structure of overburden should be established to improve the accuracy of the analysis process.Yang Ke[29] constructed a three-dimensional analysis model of mining-induced stress shell evolution, and revealed the evolution characteristics of mining-induced stress shell and its dynamic effect on mining-induced fracture development. Based on the shell plate theory, Wanrong L et al.[30] constructed a mechanical model of an elliptical thin plate. The results show that the mechanical properties of the stress shell instability are the result of the tensile fracture of the bedrock at the top of the shell. Shabanimashcool M et al.[31] found that the stability of masonry beam-arch structure is related to the initial horizontal stress of surrounding rock, and increases with the increase of stress. Tsesarsky M[32] used FLAC software to study the stress arching mechanism under the influence of layered joints in shallow coal seams, and analyzed the roof size effect and joint spacing effect under the influence of horizontal stress distribution. Song Hongwei et al.[33] proposed that the tangential stress concentration of surrounding rock caused by coal seam mining, the formation of surrounding rock pressure arch can bear the gravity of overlying strata. Zhao Yanhai[34] studied the evolution characteristics and instability mechanism of composite pressure arch of mining overburden in shallow buried working face of Shendong mining area, and revealed the mechanism of composite pressure arch structure and mine pressure in shallow buried coal seam mining. The existing three-dimensional overburden structure model has insufficient applicability to the movement of hard overburden in large space stope of extra-thick coal seam, and it is difficult to consider the combined movement characteristics under the condition of multiple key strata structures.

Taking the 8105 working face of Tongxin Mine as the research background, this paper introduces the elastic plate theory[35] and the cylindrical shell theory[36] to establish the cylindrical shell mechanical model of the hard overburden structure of Carboniferous coal seam mining in Datong mining area, analyzes its evolution characteristics, clarifies the control effect of overburden structure characteristics on mine pressure behavior, determines the overburden structure characteristics and movement form of Carboniferous coal seam stope in Tongxin Mine, and reveals the mechanism of special mine pressure phenomenon in the working face of Carboniferous coal seam in Tongxin Mine, Combined with the plane stability theory of arch shell in elastic mechanics, the calculation formulas of critical load and ultimate span of cylindrical shell structure are derived, and the hierarchical control mechanism of multiple key strata is clarified, which provides theoretical support for the prediction and control of overburden pressure in large stope of extra-thick coal seam, and fills the research gap of quantitative analysis of three-dimensional structure of multi-key strata in hard overburden. Which provides a theoretical basis for the prevention and control of mine rock burst under similar conditions in Datong mining area.

Engineering situation

Mining technical conditions of working face

The Datong mining area is the most typical hard roof mining area in China, with mainly Jurassic and Carboniferous coal seams. The Jurassic coal seams are relatively shallow, approximately 240 to 350 m from the surface, while the Carboniferous coal seams are deeper, ranging from approximately 400 to 800 m in depth. The distance between the two series ranges from 150 to 450 m. In the Datong mining area, the interbeds between the dual-series coal seams consist of fine-grained sandstone, coarse-grained sandstone, coal seams, siltstone, medium-grained sandstone, conglomerate, and sandy mudstone. Among these, the thickness of sandy lithologic strata accounts for about 90% ~ 95%, with compressive strengths ranging from 55.20 to 65.63 MPa. The roof of coal seams 3–5# in the Carboniferous series is composed of hard rock layers, with relatively intact rock bodies and high strength.

The length of 8105 working face in Tongxin Coal Mine is 200 m, the length of roadway strike is 1700 m, the section protection coal pillar is about 38 ~ 45 m, the thickness of coal seam is 15 m, and the dip angle is 2° ~ 3°. The fully mechanized mining of fully thick top coal caving is adopted, the mining height is 3.9 m, and the mining and caving ratio is 1:2.9. The comprehensive columnar roof and its physical and mechanical parameters of 8105 working face are shown in Table 1.

Characteristics of mine pressure behavior in mining faces

The thickness of the 3–5# coal seam in Carboniferous main mining is 14–20 m, and the full thickness of top coal caving mining is adopted at one time. The space of coal seam mining is large, and the mining influence is wide. During the mining of the working face, the mine pressure is strong, the shrinkage of the support and the opening rate of the safety valve are obviously increased, and support crushing accidents frequently occur. When an extrathick coal seam is mined, roof subsidence, floor heave, side heave and floor cracks in the roadway frequently occur, and the deformation of the roadway and damage to a single pillar are severe.

In the 8105 working face, a total of 25 strong mine pressure phenomena occurred during the production of the 3–5 # coal seam of the Carboniferous system. Among them, there were three impact-type dynamic disasters, which were manifested as roof subsidence, serious floor heave, bending and toppling of single column, and

Serial number	Name of rock stratum	Observed thickness/m	Volume force kN/m^3	Tensile strength/MPa	Elastic modulus/GPa
Y24	Fine-grained sandstone	6.2	27.54	8.64	35.87
Y23	Coarse-grained sandstone	14.3	25.24	6.44	21.31
Y22	Fine-grained sandstone	10.7	26.82	7.01	36.12
Y21	Sandy mudstone	2.9	26.51	4.14	18.56
Y20	Conglomerate	5.1	27.15	3.92	28.42
Y19	Sandy mudstone	6.9	25.98	5.81	18.46
Y18	Siltstone	10.5	25.20	4.52	23.17
Y17	Fine-grained sandstone	10.3	26.51	7.87	36.01
Y16	Conglomerate	4.6	26.95	4.23	28.64
Y15	Fine-grained sandstone	10.7	27.17	7.93	35.21
Y14	Siltstone	3.2	24.58	4.45	23.48
Y13	Medium-grained sandstone	13.7	25.52	7.01	29.62
Y12	Conglomerate	12.0	27.10	4.34	28.74
Y11	Coarse-grained sandstone	3.5	23.89	5.24	19.98
Y10	Conglomerate	12.9	27.35	4.34	28.43
Y9	Fine-grained sandstone	14.8	25.62	8.2	35.62
Y8	Coarse-grained sandstone	4.3	24.21	4.82	20.32
Y7	Siltstone	2.4	25.78	4.25	23.35
Y6	Shan 4 coal	2.1	10.36	1.27	0.42
Y5	Siltstone	5.3	26.45	4.97	23.64
Y4	Fine-grained sandstone	2.1	27.12	7.81	35.54
Y3	Medium-grained sandstone	7.7	26.73	6.14	29.57
Y2	K3sand	5.3	25.44	7.68	36.21
Y1	Sandy mudstone	3.2	26.31	5.47	18.35
3–5 coal seam		15.0	17.70	8.64	35.87

Table 1. Comprehensive columnar and its physical and mechanical parameters of 8105 working face in tongxin coal mine.

Fig. 1. Strong mine pressure behavior of 8105 working face.

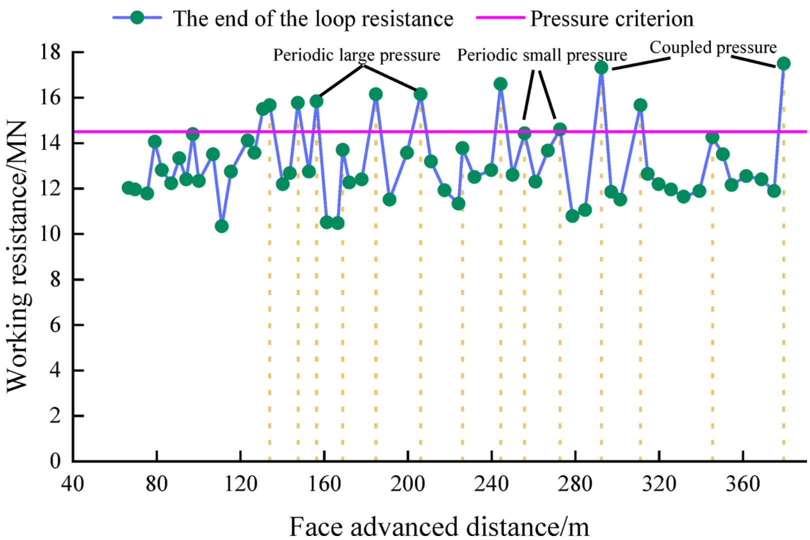

Fig. 2. Circulation end resistance curves of support No. 48 in panel 8105.

serious side heave of coal mining, as shown in Fig. 1. The field monitoring of mine pressure in working face and gob-side entry shows that the mine pressure in working face has the phenomena of periodic large pressure, periodic small pressure, strong mine pressure (multiple key strata are coupled and broken at the same time, resulting in strong mine pressure or dynamic pressure) and dynamic pressure composite, as shown in Fig. 2. The mine pressure is strong in the range of about 200 m behind the working face and about 100 m in front of the working face.

The field mine pressure monitoring results indicate the presence of a "large overlying structure" in the thick hard roof coal seam working face. This structure evolves continuously as the working face advances, causing periodic pressure and even dynamic pressure phenomena. On both the strike and dip profiles of the working face, the spatial morphology of this large structure appears as a hyperbolic flattened shell. The main factor influencing the manifestation of mine pressure on the working face is the periodic instability of the arch-shaped structure in the direction of face advancement. Therefore, the "hyperbolic flattened shell-type overlying large structure" of the thick hard roof coal seam can be simplified as an evolving column shell structure. Its formation, evolution, and instability control the intensity and scope of mine pressure manifestation on the working face.

Structural characteristics of the cylindrical shell of hard overlying rock

Movement characteristics of hard overburden rock and the evolution process of cylindrical shell structures

Based on the mining conditions of the 8105 working face in the Tongxin Coal Mine, research indicates the following movement characteristics of the hard roof: Subcritical Layer I plays a controlling role in the initial and periodic pressure on the working face, leading to minor periodic pressure. A subcritical layer II rupture at higher levels causes significant periodic pressure on the working face. Rupture of the main key layer results in intense mine pressure manifestation or dynamic pressure manifestation over a large area in front of and behind the Carboniferous series working face. The process of roof fracturing in the working face is illustrated in Fig. 3.

Before the instability of the cylindrical shell structure, the fracture of the over-lying low key strata of the 3–5# coal seam produces periodic small pressure and pe-riodic large pressure. At this time, the mine pressure

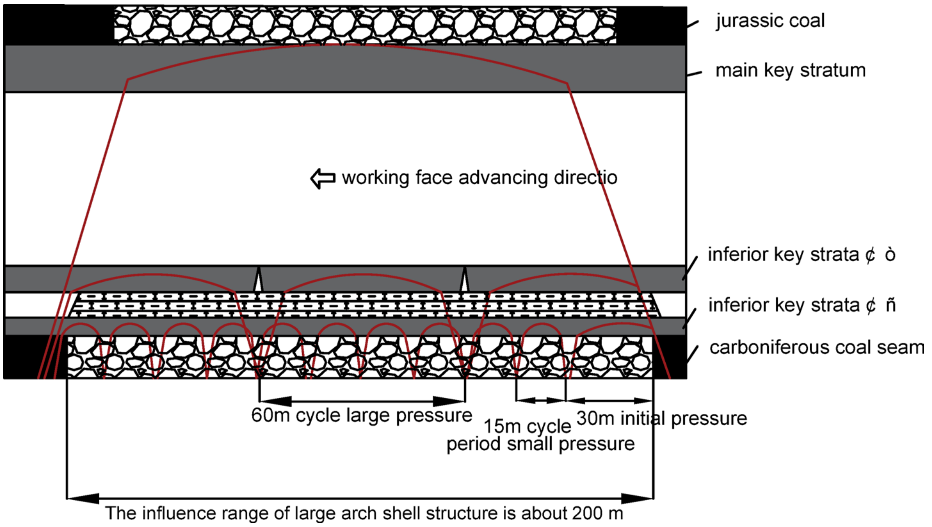

Fig. 3. Development and formation of a panel cylindrical shell structure with a multilayer of hard rock.

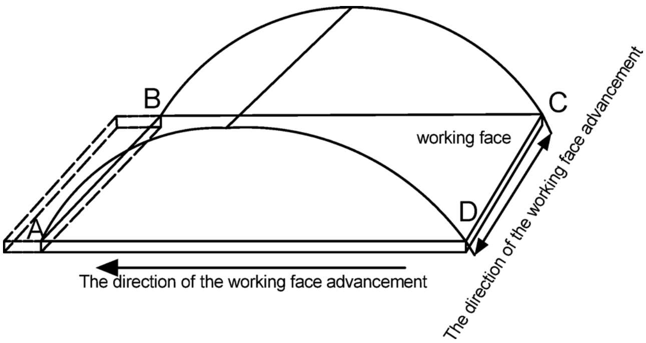

Fig. 4. Overburden structure model of the panel.

is not strong because the over-lying load is mainly borne by the cylindrical shell structure. As the working face continues to advance, when the main key stratum reaches the breaking span, the elastic energy accumulated on the cylindrical shell structure is the largest. When the working face continues to advance, the cylindrical shell structure is destroyed, and the accumulated elastic energy is suddenly released. At the same time, the load of the granular overburden rock in the goaf of the Jurassic coal seam group adjacent to the cylindrical shell structure also moves downward. Under the combined action of the two, strong mine pressure or dynamic pressure appears in a large area of the Car-boniferous working face and the front and rear of the working face, and the energy is released after the cylindrical shell structure is destroyed.

Cylindrical shell structure model and mechanical model

The cylindrical shell structure model is shown in Fig. 4. Its thickness is much smaller than the span and vector height of the section arch, which can be analyzed by thin shell theory. The solution theory for thin shells includes moment theory and nonmoment theory. The nonmoment theory assumes that there is no bending moment or torque on any cross section of the thin shell, only the internal force of the membrane, and that there is a bending moment on the cross section of the supporting pressure shell. Therefore, the moment theory of the shell is used for analysis.

The selection of the coordinate system and the direction of the internal force of the unit are shown in Fig. 5. Taking x and θ as coordinates, the Lame coefficient $A_1 = 1$, $A_2 = a$, and the principal curvature are obtained. $1/R_1 = 0$,$1/R_2 = a$,Substitute into the relevant formula of thin shell theory to obtain the cylindrical shell flat. The equilibrium differential equation is:

$$\frac{\partial T_1}{\partial x} + \frac{1}{a}\frac{\partial S}{\partial \theta} + q_1 = 0 \tag{1}$$

$$\frac{\partial S}{\partial x} + \frac{1}{a}\frac{\partial T_2}{\partial \theta} - \frac{1}{a}\left(\frac{1}{a}\frac{\partial M_2}{\partial \theta} + 2\frac{\partial H}{\partial x}\right) + q_2 = 0 \tag{2}$$

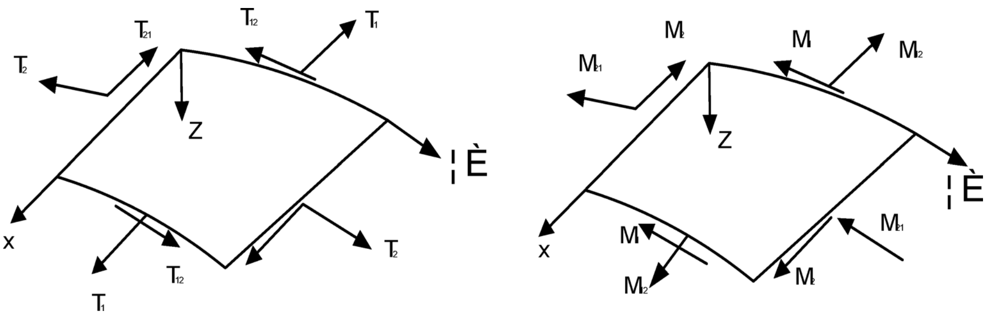

Fig. 5. Directon and coordinate of the internal force in the unit.

f/L	Two-hinged arch	Hingeless arch
0.1	28.5	60.7
0.2	45.4	101.0
0.3	46.5	115.0
0.4	43.9	111.0
0.5	38.4	97.4

Table 2. Arch shell stability coefficient values.

$$\frac{\partial^2 M_1}{\partial x^2}+\frac{2}{a}\frac{\partial^2 H}{\partial x \partial \theta}+\frac{1}{a^2}\frac{\partial^2 M_2}{\partial \theta^2}-\frac{T_2}{a}-q_n=0 \tag{3}$$

where T_1 and T_2 are the tensile pressures; T_{12} and T_{21} are the shear forces; M_1 and M_2 are the bending moments; M_{12} and M_{21} are the torques; $S=T_{12}+\frac{M_{21}}{R_2}$; $H=\frac{1}{2}(M_{12}+M_{21})$ and q_1, q_2, q_n are x, θ and the normally distributed loads, respectively.

The elastic constitutive relation is:

$$\begin{cases} T_1=\frac{Eh}{1-\mu^2}(\varepsilon_1+\mu\varepsilon_2), T2=\frac{Eh}{1-\mu^2}(\varepsilon_2+\mu\varepsilon_1), \\ M_1=D\left(k_1+\mu k_2\right), M_2=D\left(k_2+\mu k_1\right), \\ S=\frac{Eh}{2\left(1+\mu\right)}\omega, H=D\left(1-\mu\right)\tau, \end{cases} \tag{4}$$

where μ is the elastic modulus, μ is Poisson's ratio, h is the thickness of the cylindrical shell, $\varepsilon_1, \varepsilon_2, \omega, k_1, k_2, \tau$ are the six deformation components, and $D=\frac{Eh^2}{12(1-\mu^2)}$.

The geometric relation is:

$$\begin{cases} \varepsilon_1=\frac{\partial u_1}{\partial x}, \varepsilon_2=\frac{1}{a}\left(\frac{\partial u_2}{\partial \theta}+\omega\right), \omega=\frac{\partial u_2}{\partial x}+\frac{1}{a}\frac{\partial u_1}{\partial \theta}, \\ k_1=\frac{\partial^2 \omega}{\partial x_2}, k_2=\frac{1}{a^2}\left(\frac{\partial^2 \omega}{\partial \theta^2}-\frac{\partial u_2}{\partial \theta}\right), \tau=\frac{1}{a}\left(\frac{\partial^2 \omega}{\partial x \partial \theta}-\frac{\partial u_2}{\partial x}\right). \end{cases} \tag{5}$$

The boundary condition is that the displacement at the intersection of the cylindrical shell and the coal seam floor is zero, that is, the displacement on the AB and CD edges is shown in Fig. 3.$u_1=0, u_2=0, \omega=0$.

Stability analysis of the cylindrical shell structure

According to the plane stability theory of the arch, the abutment pressure arch is derived.

$$q_\sigma=K\frac{(\alpha E)\,I}{L^3} \tag{6}$$

where K is the stability coefficient of the arch shell[37], Table 2 shows the values. L is the span of the arch shell; f is the real height of the arch; E is the elastic modulus of the arch; α is the nonuniformity coefficient of the arch shell material, and the rock material is 0.1 ~ 0.3; and I is the moment of inertia of the arch section when the arch is bent in its own plane, $h^3/12$, where h is the thickness of the arch shell (according to the effective thickness of the key layer).

Application example

Relationship between cylindrical shell structure characteristics and abutment pressure arch

Based on the analysis of the column shell structure, it can be considered that the arching action of the column shell foot acts on the coal wall in front of the working face, forming a supporting pressure arch. This structural feature will play a dominant and controlling role in the manifestation of mine pressure on the working face. According to the formula for calculating the critical load of the supporting pressure arch (6), if the load remains constant, the formula for the ultimate span of the arch can be derived.

$$L_{\max} = \sqrt[3]{KaEI/q_{cr}} \tag{7}$$

Calculation of the ultimate span of subcritical layer II

Subkey stratum II of the roof overburden in the 8105 working face of the Tongxin Mine is 150 m away from the main key stratum. The elastic modulus of the rock is 20.5 GPa, and the elastic modulus of the rock mass is 15% of the elastic modulus of the rock (0.15). The thickness of subkey stratum II is 8 m, according to the definition of ' effective bearing thickness ' in the critical layer theory[7] proposed by academician Qian Minggao. the effective thickness of the abutment pressure arch is 60% of the thickness of subkey stratum II, and the section moment of inertia of the arch is 9.21. When periodic pressure is applied, the abutment pressure arch is considered a two-hinged arch, and the stability coefficient K is 38.4. The load on the overburden pressure arch structure is the overburden weight between subkey stratum II and the main key stratum. The bulk density of the rock mass is calculated to be 26.25 kN/m^3. Then, according to Eq. (7) can get:

$$L\max = \sqrt[3]{K\alpha \mathrm{EI}/q_{cr}} = \sqrt[3]{38.4 \times 0.15 \times 20.5 \times 10^9 \times 9.21/(3.94 \times 10^6)} = 65.11m \tag{8}$$

During the mining process of the 8105 working face in the Tongxin Mine, actual monitoring revealed that the step distance for periodic large pressure occurrences was 60 to 65 m. The calculated results are basically consistent with the actual manifestation of mine pressure.

Calculation of the ultimate span of the main key layer

The main key stratum of the roof overburden in the 8105 working face of the Tongxin Mine is 300 m away from the surface. The elastic modulus of the rock is 25.4 GPa, and the elastic modulus of the rock mass is 20% of the elastic modulus of the rock (0.2). The thickness of the main key stratum is 25 m, the effective thickness of the abutment pressure arch is 70% of the thickness of the main key stratum, and the section inertia moment of the arch is 446.61. When periodic pressure is applied, the abutment pressure arch is considered a two-hinged arch, and the stability coefficient K is 38.4. The load borne by the overburden pressure arch structure is the weight of the overburden from the main key stratum to the surface. The bulk density of the rock mass is calculated to be 26.25 kN/m^3. Then, according to Eq. (7),

$$L\max = \sqrt[3]{K\alpha \mathrm{EI}/q_{cr}} = \sqrt[3]{38.4 \times 0.2 \times 25.4 \times 10^9 \times 446.61/(7.88 \times 10^6)} = 222.77m \tag{9}$$

During the mining process of the 8105 working face in the Tongxin Mine, strong dynamic pressure phenomena occurred in localized areas of the working face, and intense mine pressure manifestations were observed behind the working face, at a distance of 200 m in the empty roadway, and 70 to 80 m ahead of the working face. According to the analysis of the calculation results, this phenomenon was caused by the instability resulting from the rupture of the main key layer.

Conclusions

(1) The Carboniferous extrathick coal seam in the Tongxin Coal Mine is covered with a thick hard roof. Plate, fully mechanized caving mining to form a large stope space. Mine pressure has a large impact on stress and has the characteristics of large and small periodic pressures and dynamic pressure phenomena. Stope The structural characteristics of the overlying rock and its movement on the working face and gob-side entry significantly influence the regional rock pressure.

(2) The influence of working face mining in extra thick coal seam on the movement and instability process of overlying hard rock strata is analyzed. The mechanical model of ' large structure of overlying rock column shell ' is established by using elastic plate theory, and the mechanical equilibrium condition of ' large structure of overlying rock column shell ' is determined. The calculation formula of critical load of roof structure is given, and the limit span of cylindrical shell structure is calculated, which provides a theoretical basis for the analysis of mine pressure appearance and dynamic pressure phenomenon of hard roof in Datong mining area.

(3) The analysis and calculation results well explain the characteristics of mine pressure in Tongxin mine. The application verification of the model shows that the calculation results are in good agreement with the actual height of the project : the calculation value of the limit span of the sub-critical layer II of the 8105 working face is 65.11 m ; the calculated limit span of the main key stratum is 222.77 m, and the large and small periodic weighting generated by the 8105 working face is affected by the sub-key stratum. The composite mine pressure phenomena such as strong mine pressure appearance and dynamic pressure appearance in the working face and the characteristics of large spatial range of mine pressure influence in front and back of the working face are mainly controlled by the instability and breaking of the main key strata.

(4) The model is suitable for the fully mechanized caving mining conditions of 'hard overburden + extra-thick coal seam ', especially for the mining area (Datong mining area) with multi-layer thick and hard key strata, which can scientifically reveal the characteristics of overburden movement and the law of mine pressure appearance ; subsequently, the discrete element method can be introduced to construct a numerical model of ' cylindrical shell structure-fractured rock mass ' to quantify the influence of heterogeneous fractures on the instability of cylindrical shells.
(5) The calculation method of ' overburden cylindrical shell structure ' of thick and hard roof of Carboniferous coal seam in Datong mining area is determined, which provides a way for the analysis of instability movement and mine pressure characteristics of hard rock strata under similar conditions.

Data availability

All data generated or analysed during this study are included in this pub-lished article.

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Declarations

Competing interests
The authors declare no competing interests.

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