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# A NEW METHOD TO CONTROL THE REGIONAL STRATA MOVEMENT OF SUPER-THICK WEAK CEMENTATION OVERBURDEN IN DEEP MINING

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## ABSTRACT

In the western of China, the deep mining area with super-thick and weak cementation overburden is vast, sparsely populated and the ecological environment is extremely fragile. With the large-scale exploitation of deep coal resources, it is inevitable to face green mining problem, whose essence is the surface subsidence control. Therefore, it is necessary to study the control technology for the regional mining based on the evolution law of subsidence movement and energy-polling of super-thick and weak cementation overburden, and put forward the economically design scheme that can control strata movement and surface subsidence in a certain degree. Based on the key strata control theory, this paper puts forward the subsidence control scheme of partial filling -partial caving in multi-working face coordinated mining, and further studies its control mechanism through the numerical simulation and then analyzes the control effect of the strata movement and energy-polling in the fully caving mining, backfill mining, wide strip skip-mining and mixed filling mining method etc., the following conclusions are detailed as follows: (1) The maximum value of energy-polling occurs on the coal pillars or on both sides of goaf. With the width of goaf, the maximum value of energy-polling increases in a parabola. (2) In the partial filling-partial caving multiple working faces coordinated mining based on the main key stratum, the stress distribution of the composite backfill in the filling working face is parabolic, and it is high on both sides and low in the middle. Moreover, in the composite backfill, the stress concentration degree of a outside coal pillar is greater than that of the inside coal pillar. (3) The control mechanism of partial filling-partial caving harmonious mining based on main key layer structure is the double-control cooperative deformation system, formed by the composite backfill and the main and sub-key layers structure. They jointly control the movement and energy accumulation of overlying strata by greatly reducing the effective space to transmit upward, and absorb the wave subsidence trend of the overburden until it develops into a single flat subsidence basin. (4) Considering the recovery rate, pillar rate, area filling rate, technical difficulty and subsidence coefficient etc., the partial filling-partial caving multiple working faces coordinated mining based on the main key stratum is the most cost-effective mining method to control surface subsidence. This paper takes a guiding role in

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controlling the regional strata movement and surface subsidence of deep mining with super-thick and weak cementation overburden.

## KEYWORDS

Deep filling mining, Regional control, Key stratum, Numerical simulation

## INTRODUCTION

With the westward development of China economic strategy, Ordos coalfield has become an important area where supplies the country's energy needs. It has simple geological structure and abundant deep coal resources, which is suitable for large-scale mining with high intensity. At present, many scholars have studied on the strata movement of deep mining in Ordos coal field, and achieved certain results. For example, Wang [1] and Lin [2] studied the movement law of weak cementation overburden of deep single working face mining by means of physical simulation and numerical simulation method, and believed that the control effect of super-thick weak cementation sandstone was the reason for the small surface subsidence. By analyzing the surface measured data of Yingpanhao Coal mine, Zhang believed that the main reasons for the abnormal characteristics of the overburden movement were that the dip direction did not reach sufficient mining and the super-thick weak cementation sandstone has a strong control effect [3]. Gong used multi-borehole strata data to construct intensive 3D numerical model to study the movement law of super-thick weak cementation sandstone in deep mining, and results show that Zhidan group sandstone has a strong control effect, which makes the surface subsidence smaller under the same mining conditions [4]. In addition, he also studied the influence of joint and block size on the motion law and failure characteristics of the super-thick weak cementation sandstone [5]. Ning found that the periodic pressure of working face is closely related to the breaking law of main roof and key stratum in Nalinhe coal mine [6]. Wang carried out in-depth research on the occurrence mechanism and prevention of typical dynamic disasters in deep mining, and believed that the fracture of low-hard stratum and high thick sandstone was one of the main causes resulting in rock burst and mine quake [7]. The writer uses similar material simulation method to study the failure law of super-thick weak cementation sandstone, and results show that it has a larger limit span and strong control effect, and its failure characteristics are "arch shell - beam - half arch shell - step" [8]. In the meanwhile, the numerical simulation method is used to study the compound effect of super-thick weak cementation sandstone, and explored the influence law of its spatial location and thickness on the failure characteristics and energy accumulation of the overburden [9].

The above research shows that the high intensity mining of coal resources in deep mining area of Ordos coal field is faced with many problems. With the mining depth increasing and the mining scope expanding in Ordos coalfield, rock burst, mine earthquake and other disasters occur frequently caused by the special strata movement and energy accumulation of the super-thick weak cementation sandstone, and the serious surface subsidence leads to the deterioration of ecological environment. These phenomena have become a serious problem restricting the large-scale continuous mining of coal mines. Therefore, it is necessary to study a kind of efficient, safe and green mining technology to control the strata movement and energy accumulation of super-thick sandstone and alleviate mine quake and surface subsidence disaster.

The current normally used subsidence control technologies mostly include surface subsidence control technologies with filling bodies as the core and surface subsidence control technologies with coal-rock bodies as the core. Strip mining and goaf filling mining are presently frequently used approaches for controlling surface subsidence. The principle of strip mining is to divide the coal seam into regular shapes, mining one and leaving one, and the remaining coal pillars can bear the load of the overlying strata, thereby controlling the surface movement and deformation. In other aspect, backfill mining is to control the surface deformation by filling the mined-out area with filling bodies, reducing the sinking space. The research on the control mechanism of these two means has been relatively mature and has been extensively applied in eastern mining areas.

In addition, with coal pillar-overburden structure collaborative deformation, researchers have sequentially proposed coal pillar compression and indentation theory [10], rock beam hypothesis [11], plate theory [12-14] and other rock control theories. Plate theory suggests that surface subsidence is composed of coal pillar compression deformation, overburden compression deformation and plate deflection. Meanwhile, it is believed that the synergy of coal pillars and plates has effectively controlled surface subsidence. With the increase of mining depth, the question of coal pillar-overburden structure coordinated deformation in deep mining has gradually changed from the issue of coal pillar-roof cooperative deformation to the problem of coal pillar-high control layer cooperative deformation, and coal pillar stability question has gradually changed from the issue of the stability of coal pillar itself to the overall stability of coal rock pillar structure, which is often affected by adjacent or multiple working faces (goafs). Scholars such as Chen Junjie [15], Guo Weijia [16,17], Zhang Ming [18] and Jiang Fuxing [19] have performed substantial researches on the stability of coal pillars in deep strip mining and the control of subsidence mechanism.

In terms of backfill mining, the Xiaotun Mine, Daizhuang Mine and other mining areas applied paste materials as filling materials for longwall filling mining. Huafeng Mine and Quangou Mine utilized general working face gangue to fill the goaf to liberate coal resources under the building (structure) and to reduce the amount of solid waste exiting the well [20]. Dongping Mine, Jisan Mine and other mining areas adopted solid-bakcfill mining technology to liberate a large amount of coal resources under the building and consumed significant solid waste [21-23].

With regard to the combination of strip mining and backfill mining, Guo Guangli proposed to apply the equivalent replacement theory and adopt the method of ‘Gradually taking ‘. First, the narrow strip was implemented, and then the narrow strip goaf was injected. The idea of slurry filling ultimately achieves the purpose of recovering the remaining coal pillars [24]. Zhang Huaxing suggested the wide strip mining method of " Large mining width-wide retention width-goaf filling", offering a new idea for liberating the deep coal resources of "three under" [25,26]. Li Xiushan and Zhang Xinguo took Daizhuang coal mine as an instance to investigate the feasibility of using paste as a filling material and adopting filling technology to recover strip coal pillars. The outcomes indicate that the filled paste has strong stability and can replace coal seam to bear the overburden load [27,28]. With Gaozhuang as an example, Hou Xiaosongexplored the feasibility of pillarless mining in practice. The study gave that backfilling the roadway with gangue concrete grout can be utilized to recover the coal pillars between the roadway and the channel while ensuring the stability of the surrounding rock. This method further reduces the waste of resources and improve the resource utilization rate [29]. Zhang Xinguo learned the mining mode of driving the roadway in the strip coal pillars and filling and recovering the strip coal pillars based on Xuchang coal mine. The research indicated that although the safety factor is reduced after the roadway is driven in the middle of the strip coal pillars. However, the composite backfill formed by the roadway gangue and the remaining coal pillar still has a strong bearing capacity and can effectively control surface deformation [30].

From the above researches, the current investigation on the control of surface subsidence largely focuses on the coal mining of “three under“in the east, while the research on the regional rock movement and its control of the super-thick weak cementation overburden in deep mining in the western of China is rarely mentioned. The "three-under" coal mining surface subsidence control method can be employed to control the regional strata movement in deep mining of the western super-thick weak cementation overburden, but the deep mining area of the western super-thick weak cementation overburden is wide and sparsely populated. The control plan of "three under" will generate substantial waste of coal resources and high filling costs.

Thus, this paper combines the movement law and energy evolution of super-thick weak cementation overburden in deep mining, and proposes an economical design plan that can control the regional movement to a certain extent.

## Evolution law of energy-polling of super-thick weak cementation overburden in deep mining

The existing results suggest that when the mining area is small and the surface is in an extremely inadequate mining state, the surface subsidence of the super-thick weak cementation overburden is noticeably smaller. With the continuous expansion of the mining area, the overburden has a sudden and jumping sinking phenomenon. Thus, during the movement of the overlying strata, energy-polling and release must exist. According to the analysis of the energy-polling and evolution characteristics of the super-thick weak cementation overburden, this chapter describes a reasonable mining plan in combination with the law of movement and failure characteristics of the super-thick weak cementation overburden, thereby reducing the dynamic strength and surface damage degree. This mining plan provides a reference for the layout of the working face in the deep mining area, facing the control of regional strata movement.

This section chiefly applies elastic energy as the representative quantity to learn the evolution law of energy-polling of super-thick weak cementation overburden in deep mining.

Based on Ref. 31, when coal and rock mass damage is not considered, the releasable elastic energy can be expressed as the following formula:

$$U^e=\frac{1}{2}\sigma_1\varepsilon_1^e+\frac{1}{2}\sigma_2\varepsilon_2^e+\frac{1}{2}\sigma_3\varepsilon_3^e \qquad （1）$$

Where：$\varepsilon_i^e$ is the total elastic strain in the three principal stress directions, $\varepsilon_i^e=\frac{1}{E_i}\left[\sigma_i-\vartheta_i\left(\sigma_j+\sigma_k\right)\right]$, $\vartheta_i$ is the poison's ration.

Substituting the expression $\varepsilon_i^e$ into Eq. (6-1), Eq. (6-2) can be obtained [32]:

$$U^e=\frac{1}{2}\left\{\frac{\sigma_1^2}{E_1}+\frac{\sigma_2^2}{E_2}+\frac{\sigma_3^2}{E_3}-\vartheta\left[\left(\frac{1}{E_1}+\frac{1}{E_2}\right)\sigma_1\sigma_2+\left(\frac{1}{E_2}+\frac{1}{E_3}\right)\sigma_2\sigma_3+\left(\frac{1}{E_1}+\frac{1}{E_3}\right)\sigma_1\sigma_3\right]\right\} \qquad （2）$$

For damaged rock mass, unloading of rock mass will have an impact on the elastic modulus:

$$E_i=a_iE_0 \qquad （3）$$

Where, $E_0$ is the initial elastic modulus when the unit body is not damaged, and $a_i$ is the reduction coefficient.

Assuming that the poison's ratio "$\vartheta$" is not affected by rock damage, substituting Eq. (3) into Eq. (2), we can get:

$$U^e=\frac{1}{2E_0}\left\{\frac{\sigma_1^2}{a_1}+\frac{\sigma_2^2}{a_2}+\frac{\sigma_3^2}{a_3}-\vartheta\left[\left(\frac{1}{a_1}+\frac{1}{a_2}\right)\sigma_1\sigma_2+\left(\frac{1}{a_2}+\frac{1}{a_3}\right)\sigma_2\sigma_3+\left(\frac{1}{a_1}+\frac{1}{a_3}\right)\sigma_1\sigma_3\right]\right\} \qquad （4）$$

For the convenience of calculation, the paper ignores the influence of unloading damage on the elastic modulus and Poisson's ratio, then Eq. (4) can be expressed as Eq. (5) [33]:

$$U^e=\frac{1}{2E_0}\left[\sigma_1^2+\sigma_2^2+\sigma_3^2-2\vartheta(\sigma_1\sigma_2+\sigma_2\sigma_3+\sigma_1\sigma_3)\right] \qquad （5）$$

In this paper, a three-dimensional numerical model (4500m in length, 4500m in width, 763m in height) is built, and the bottom boundary of the model is selected as the constrained boundary (a=b=c=0, a is the displacement in the x direction, b is the displacement in the y direction, and c is the displacement in the z direction), the top is the free, and the left and right boundaries are constraint in the horizontal direction. The working face width is 300m, the strike distance is 2500m, the section coal pillar is 25m, and 8 working faces are continuously mined.

According to Eq. (5), the post-processing program is developed with Fish language to extract the energy value in the FLAC3D numerical model. Then, the energy value was imported into Tecplot10.0 software for display. Next, with the help of such post-processing program, the energy-polling evolution law in the movement of super-weak cementation overburden in deep mining is analyzed, such as the energy-polling distribution characteristics in Figures 1 and 2.

In Figure 1, the energy-polling was dominated by the compression strain energy after mining the first working face (working face 2101). The compression strain energy in the Zhidan group sandstone was released slightly, and the Zhidan group sandstone was not destroyed. The Zhidan group sandstone and the overburden above it were bent synchronously.

In Figure 2, the maximum energy-polling is 1300kJ after the second working face was mined, which occurs near the section coal pillar. At this time, the energy-polling is still mainly dominated by compressive strain energy. The compressive strain energy-polling occurs in the upper part of Zhidan Group sandstone above the goaf.  This is because stronger tensile failure occurs far from two sides of the goaf in Zhidan Group sandstone. Then, larger bending deformation and compression occurs in the upper strata. The overburden subsided sharply, and its load further transferred to both sides of the goaf, and the energy-polling of the coal walls on both sides of the goaf continued to increase.

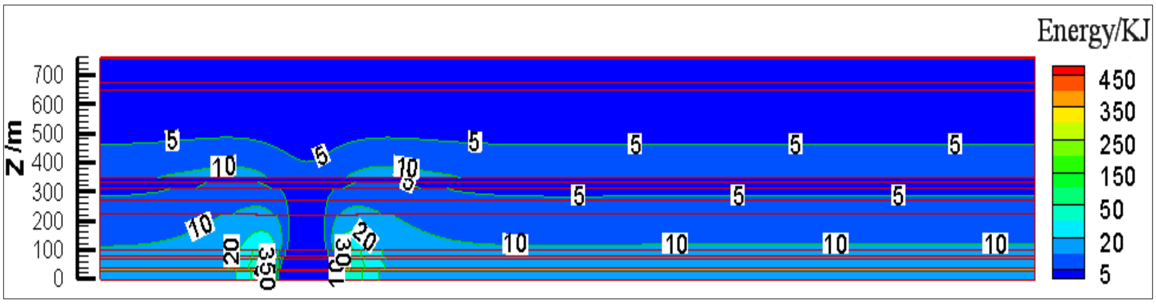


*Fig. 1 - Energy-polling distribution characteristics when one working face was mined*

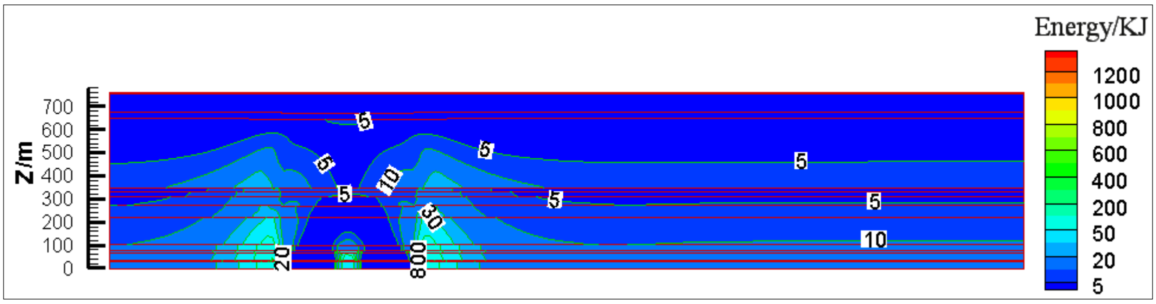
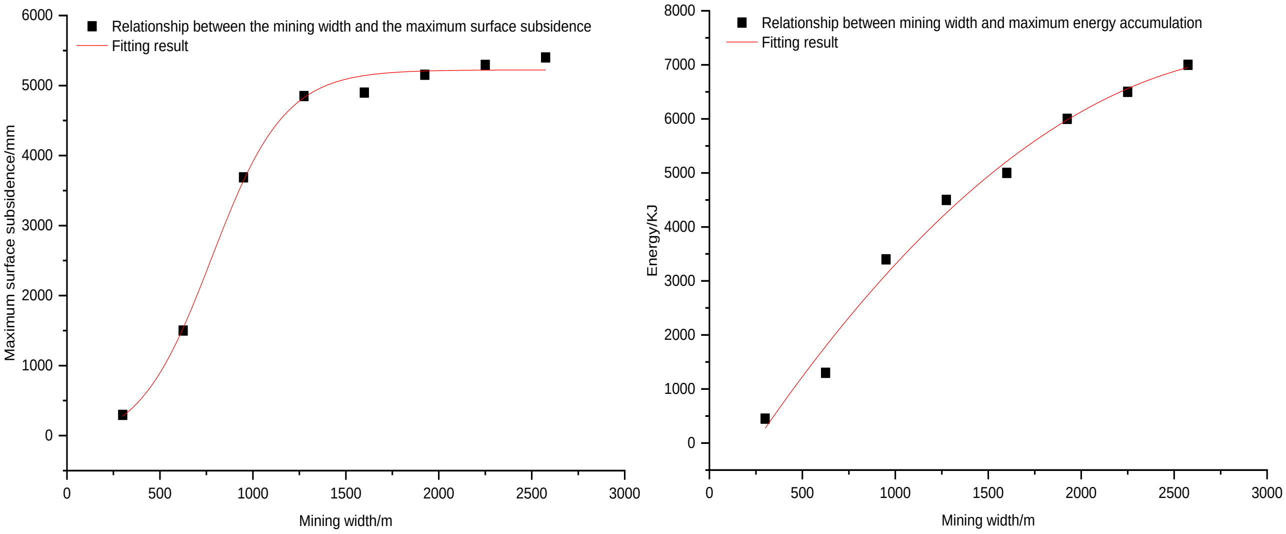


*Fig. 2 - Energy-polling distribution characteristics when two working faces were mined*

In order to visually analyze the relationship between the maximum energy-polling value and the mining width, the maximum energy-polling value in different mining width is calculated. The relationship between the mining space and the maximum energy-polling value is drawn, and the relationship between the goaf width and the maximum surface subsidence is depicted, as shown in Table 1 and Figure 3.

*Tab. 1 - Statistical table of maximum subsidence and energy-polling values*

| Mining width/m | 300 | 625 | 950 | 1275 | 1600 | 1925 | 2250 | 2575 |
|---|---|---|---|---|---|---|---|---|
| subsidence/mm | 295 | 1499 | 3689 | 4849 | 4899 | 5154 | 5295 | 5400 |
| Energy accumulation/KJ | 450 | 1300 | 3400 | 4500 | 5000 | 6000 | 6500 | 7000 |



*（a）Mining width and maximum subsidence （b）Mining width and maximum energy*

*Fig. 3- Functional relationship between mining area and maximum surface subsidence and energy-polling values*

Based on Figure 3 (a), as mining width increases, the maximum surface subsidence value gradually increases. According to the outcomes of Origin fitting, it can be seen, that the mining width is related to the maximum surface subsidence as a Boltzmann function, the correlation coefficient $R_2=0.993$, x is the mining width, and the corresponding mathematical relationship is as follows:

$$W_{max}=5223-\frac{5379}{1+e^{\frac{x-777}{196}}} \qquad (6)$$

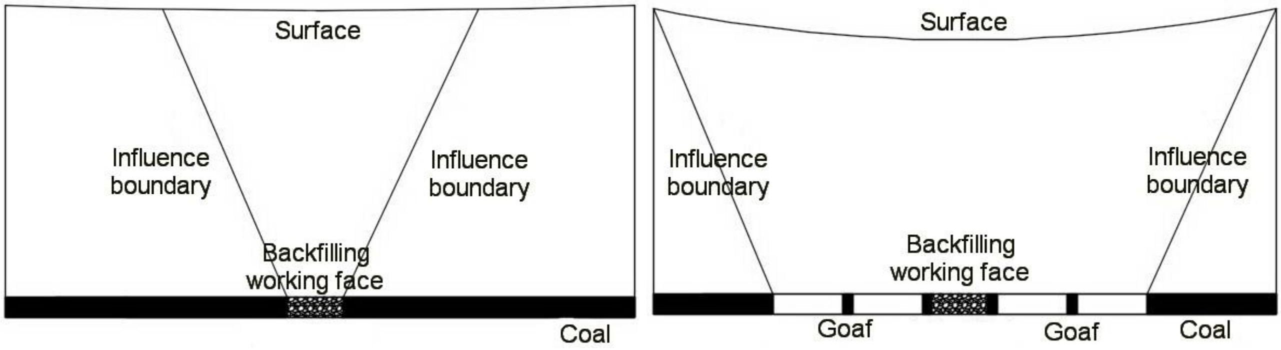
According to Figure 3 (b), as the goaf width increases, the maximum energy-polling progressively increases. From the results of Origin fitting, it can be seen, that the goaf width has a parabolic correlation with the maximum energy-polling, the correlation coefficient $R_2=0.984$, x is the goaf width, the corresponding mathematical relationship is as follows:

$$Energy_{max}=5.49x+0.001x^2-1293.5 \qquad (7)$$

From comparison, it can be found that although the mining width expands, the corresponding maximum surface subsidence value and the maximum energy-polling also increase, but the mathematical relationship between the goaf width and the maximum surface subsidence is significantly different from the mathematical relationship between the goaf width and the maximum energy-polling.

## Control plan of regional strata movement of super-thick weak cementation overburden in deep mining

Based on the characteristics of energy accumulation and failure law of overlying strata of super-thick weak cementation overburden in deep mining, the paper proposes a method of partial filling-partial caving multiple working faces coordinated mining based on the main key stratum, thereby reducing the strength of the rock dynamics and surface damage degree in the overburden, which are shown in Figure 4.



（a）Backfilling （b）Caving mining

*Fig. 4 - Schematic diagram of partial filling-partial caving harmonious mining design scheme based on main key layer structure*

First, the relevant literature can be referred to establish the physical and mechanical parameters of the gangue filling area [34], and verify the model parameters by the principle of equivalent mining height [35].

*Tab. 2 - Physical and mechanical parameters of the backfill*

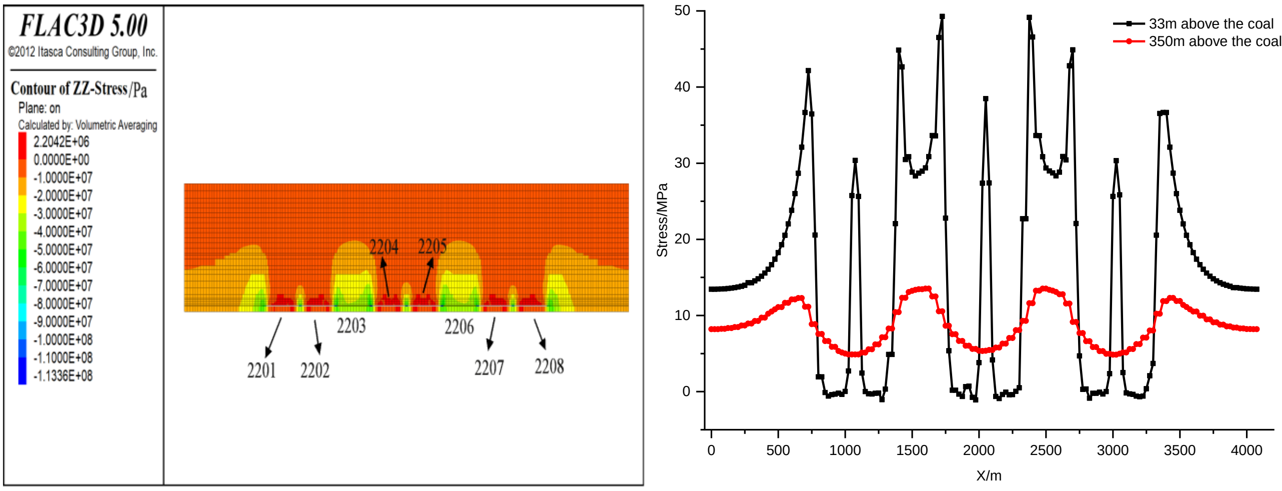
| Mechanical parameter | Bulk /Gpa | Shear /Gpa | Friction angle/(°) | Cohesion /Mpa | Density /(kg/m3) | Poisson |
|---|---|---|---|---|---|---|
| Coal | 1.35 | 0.587 | 6 | 8.89 | 1210 | 0.31 |
| Gangue filling area | 0.21 | 0.095 | 28 | 2 | 1500 | 0.3 |

Then, this paper use FLAC3D numerical simulation analysis software to carry out a method of partial filling-partial caving multiple working faces coordinated mining based on the main key stratum, a three-dimensional numerical model was established to mine 8 working faces continuously. The model and excavation parameters are shown in Table 3:

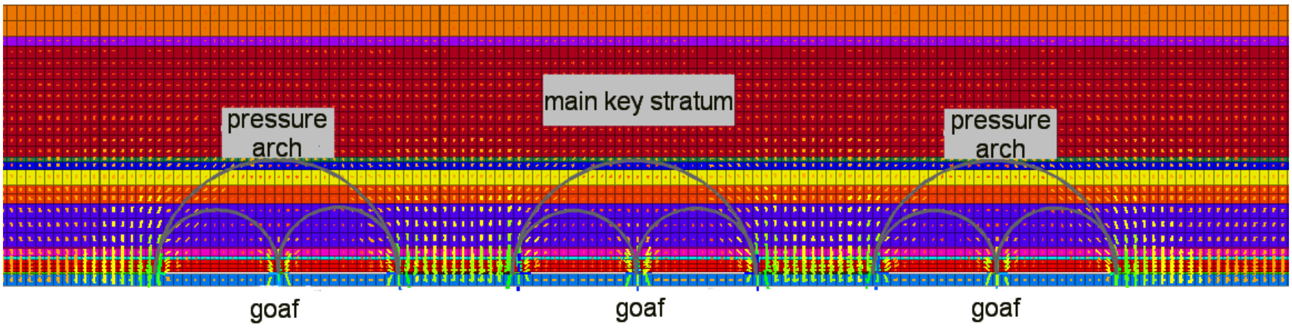
*Tab. 3 - Excavation sequence of partial filling-partial caving harmonious mining based on main control layer structure*

| Mining sequence | Working face | X direction/m | Y direction/m | Mining method |
|---|---|---|---|---|
| Second stage | 2201 | 750~1050 | 750~3250 | Caving mining |
| | 2202 | 1075~1375 | 750~3250 | Caving mining |
| First stage | 2203 | 1400~1700 | 750~3250 | Backfilling |
| Second stage | 2204 | 1725~2025 | 750~3250 | Caving mining |
| | 2205 | 2050~2350 | 750~3250 | Caving mining |
| First stage | 2206 | 2375~2675 | 750~3250 | Backfilling |
| Second stage | 2207 | 2700~3000 | 750~3250 | Caving mining |
| | 2208 | 3025~3325 | 750~3250 | Caving mining |

From numerical simulation analysis, the stress distribution characteristics of the partial filling-partial caving multiple working faces coordinated mining based on the main key stratum are shown in Figure 5:



*（a）Vertical stress contour of longitudinal section* *（b）Vertical stress in some strata*



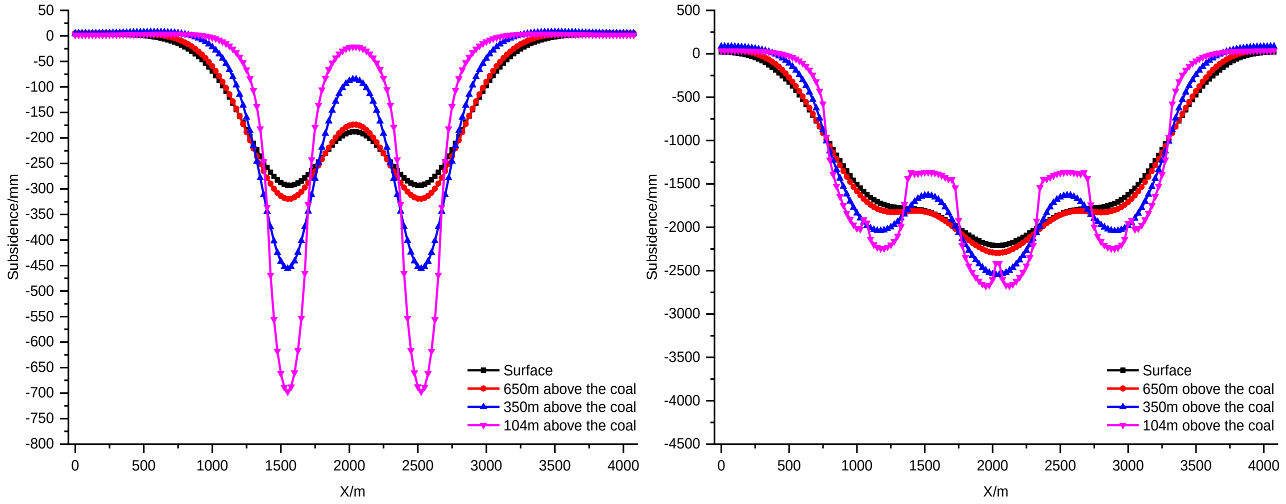
*（c）Distribution diagram of pressure arch*

*Fig. 5 - Stress field distribution diagram of partial filling-partial caving harmonious mining based on main key stratum structure*

It can be seen from Figure 5 (a) that the composite filling structure formed by the filling working face and the section coal pillar divides the entire mining area into three independent insufficient mining spaces, and acts as a wide isolated coal pillar to support the overburden load. Each independent goaf is composed of two caving working faces. After a single working face mined, the upper rock mass breaks and collapses, forming a caving fractured zone. The sub-critical stratum restricts the caving fractured zone from continuing to develop upward. The load of the sub-key stratum and its overlying strata is transferred to both sides and concentrated, forming a pressure arch in the middle-low part of the sub-key stratum. After two consecutive working faces are mined, the caving fractured zone continues to develop upwards, and the load of the main key stratum and its overlying strata is transferred to both sides and concentrated on the coal walls of both sides of the goaf, forming a large stress arch under the main key stratum. Meanwhile, a bimodal small pressure arch is formed above a single working face, and the dome develops slightly upwards, as shown in Figure 5 (c).

From Figure 5 (b), the stress distribution of the composite backfill is parabolic, high on both sides and low at the middle, and the internal stress of the composite backfill reaches 49.3MPa, which is slightly larger than the external 44.9MPa. The maximum vertical stress of coal pillars in composite backfill is greater than the maximum vertical stress of 42.2MPa on the coal walls of the goaf sides. The vertical stress of coal pillar between the working face 2204 and the working face 2205 is 38.5 MPa, and the vertical stress of coal pillar between the working faces 2201 and 2202, and the vertical stress of coal pillar between the working faces 2207 and 2208 is 30.4 MPa. The load of the overlying strata is transferred to both sides along the stress arch, and a stress release zone is formed above the goaf. The vertical stress distribution at the bottom of the main key stratum is wavy, with the maximum value of 13.5MPa and the minimum value of 4.86MPa.

In order to more intuitively analyze the strata movement in different buried depth in the method of partial filling-partial caving multiple working faces coordinated mining based on the main key stratum, the movement data of 104m, 350m, 650m above the coal seam and the surface are got and plotted as Figure 6. It can be seen from Figure 6 that as the height from the coal seam increases, the wave-shaped sinking trend gradually eases, but it still develops to the surface. This wave-shaped sinking is related to factors such as the goaf width and the width of the backfill working face.



（a）Backfilling （b）Caving mining

*Fig. 6 - Strata subsidence curve in different depth caused by partial filling-partial caving harmonious mining based on main key layer structure*

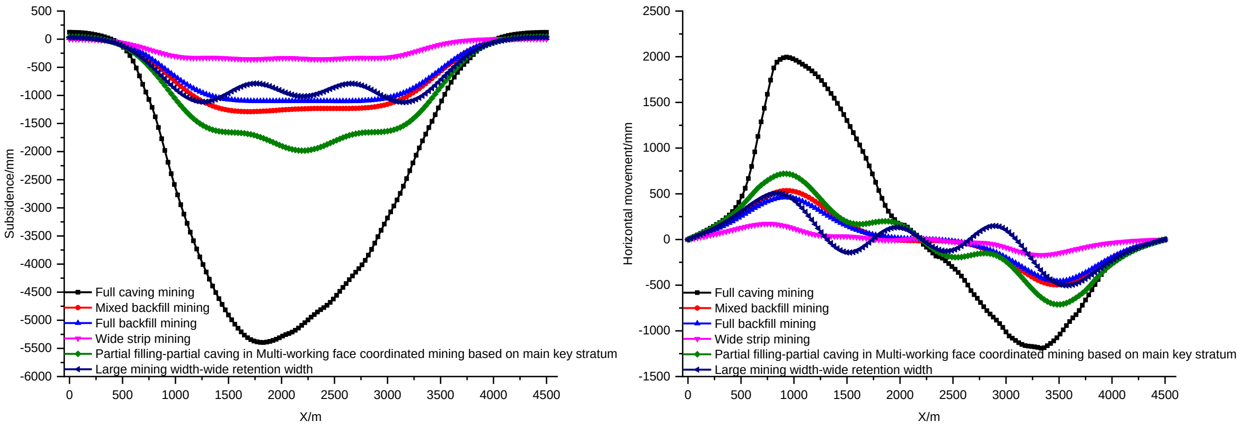
## Comparative analysis of the control effect of strata movement and energy-polling in different mining approaches

To verify the superiority of the partial filling-partial caving multiple working faces coordinated mining based on the main key stratum, full caving mining, full filling mining, wide strip mining, mixed filling mining, large mining width-wide retention width are simulated respectively, the corresponding mining plan is indicated in Table 4.

The corresponding three-dimensional numerical model can be established based on the mining plans in Table 4, and the surface subsidence value and horizontal movement value can be calculated, and the corresponding deformation curve diagram can be drawn in Figure 7. According to Eq. (5), the energy accumulation value in the corresponding numerical model can be extracted, and the corresponding energy-polling distribution feature map can be drawn through Tecplot10.0 drawing software, as shown in Figure 8.

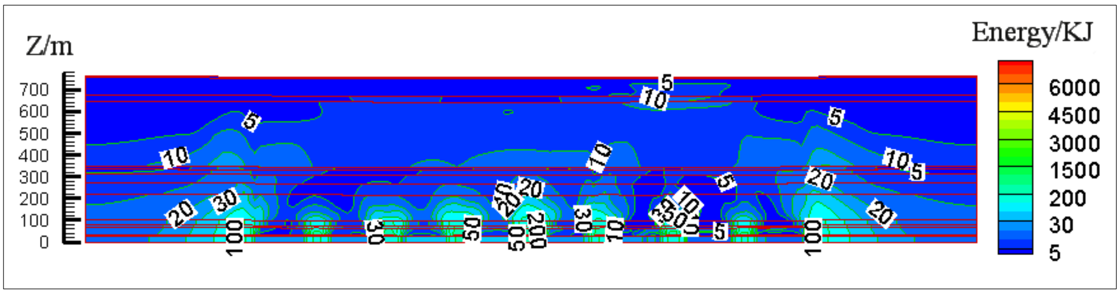
*Tab. 4 - Scheme design of different mining ways*

| Mining method | Width of caving working face | Width of backfilling working face | Filling ratio | Strike length | Coal pillar width |
|---|---|---|---|---|---|
| Full caving mining | 300 | 0 | 0% | 2520 | 30 |
| Full backfill mining | 0 | 300 | 80% | 2520 | 30 |
| Wide strip mining | 300 | 0 | 0% | 2520 | 30 |
| Mixed backfill mining | 300 | 300 | 80% | 2520 | 30 |
| Large mining width-wide retention width | 630 | 0 | 0% | 2520 | 30 |
| Partial filling-partial caving in Multi-working face coordinated mining based on main key stratum | 630 | 300 | 80% | 2520 | 30 |

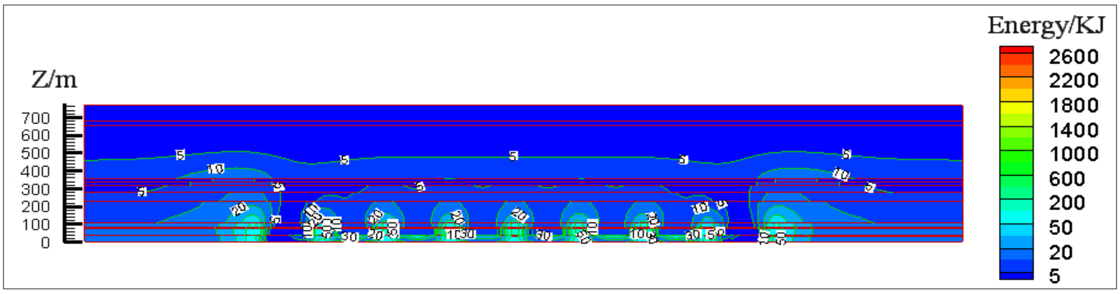


（a） Surface subsidence curve （b） Horizontal movement curve

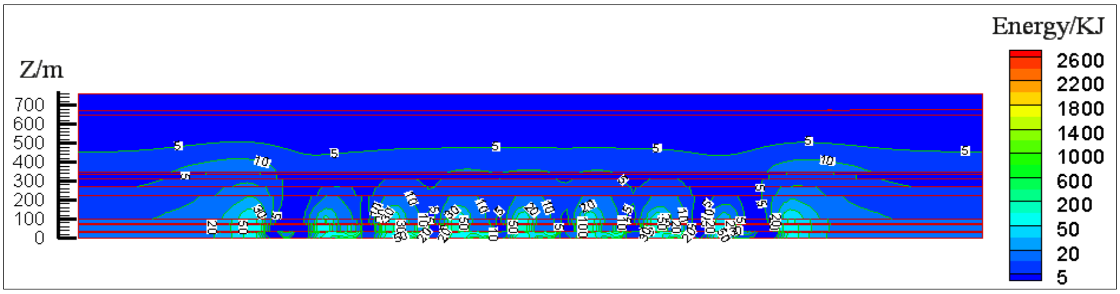
Fig. 7 - Surface movement and deformation curve of different mining ways



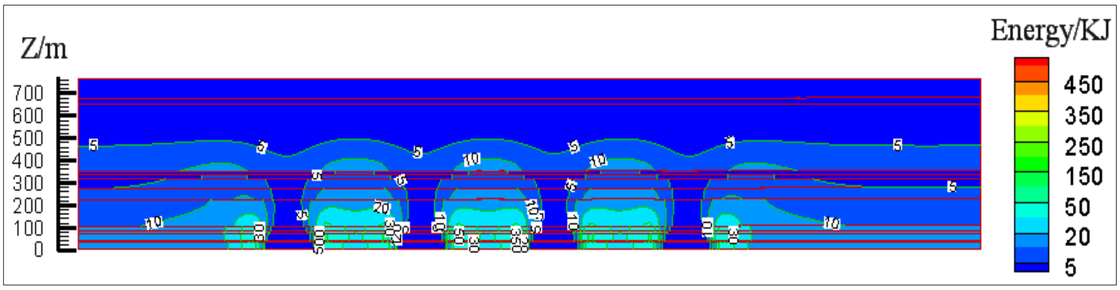
（a） Full caving mining



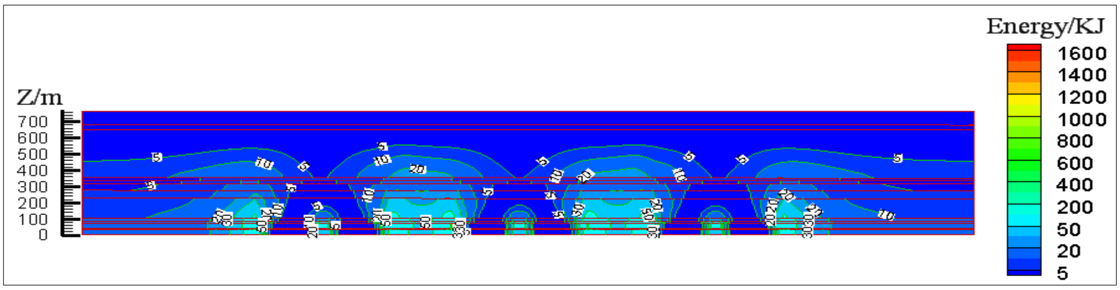
（b） Full backfill mining



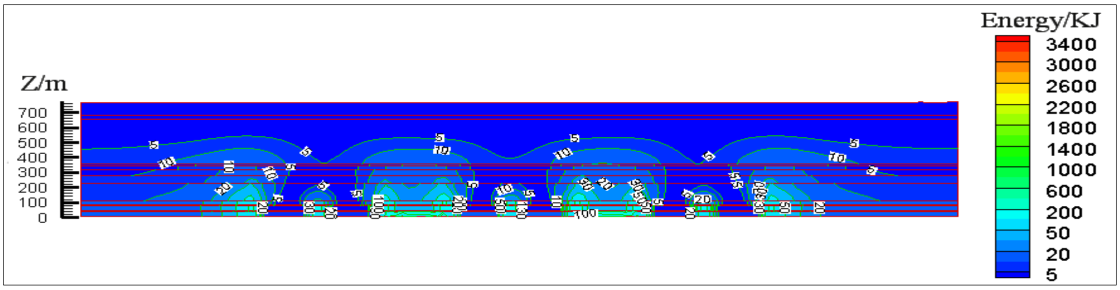
（c） Mixed backfill mining



*(d) Wide strip mining*



*(e) Large mining width-wide retention width*



*(f) Partial filling-partial caving in multi-working face coordinated mining based on main key stratum*

*Fig. 8 - Energy-polling distribution characteristics of different mining methods*

To visually analyze the surface subsidence and energy-polling of different mining means, the corresponding filling rate, recovery rate, coal pillar rate, maximum surface subsidence value and maximum energy accumulation value can be extracted and calculated (Table 5).

*Tab. 5 - Statistical table of surface subsidence and energy-polling extreme values in different mining methods*

| Mining method | Maximum subsidence /mm | Maximum energy/KJ | Filling Subsidence coefficient ratio | Area filling ratio | recovery ratio | Rate of coal pillar |
|---|---|---|---|---|---|---|
| Full caving mining | 5394 | 6000 | 0.9 | 0% | 92% | 8% |
| Full backfill mining | 1101 | 2600 | 0.18 | 92% | 92% | 8% |
| Wide strip mining | 357 | 500 | 0.06 | 0% | 46% | 46% |
| Mixed backfill mining | 1289 | 2600 | 0.21 | 46% | 92% | 8% |
| Large mining width-wide retention width | 1122 | 1600 | 0.19 | 0% | 69% | 31% |
| Partial filling-partial caving in multi-working face coordinated mining based on main key stratum | 1983 | 3400 | 0.33 | 31% | 92% | 8% |

In Table 5, from the reduction effect of the surface subsidence, it has following relationship: wide strip mining>full backfill mining>large mining width-wide retention width>mixed backfill mining> partial filling-partial caving in multi-working face coordinated mining based on main key stratum > full caving mining. From the control effect of the energy-polling, it has following relationship: wide strip mining>large mining width-wide retention width> full backfill mining = mixed backfill mining> partial filling-partial caving in multi-working face coordinated mining based on main key stratum> full caving mining. It can be assumed that the recovery rate and coal pillar rate reflect the utilization degree of coal resources, the area filling rate reflects the coal mining cost, and the subsidence coefficient reflects the damage of the ecological environment to a certain extent. With comprehensive considerations, mixed backfill mining, partial filling-partial caving in multi-working face coordinated mining based on main key stratum are the most cost-effective. Mixed backfill mining is to realize mining and backfilling at the same working face, which is technically difficult. Thus, partial filling-partial caving in multi-working face coordinated mining based on main key stratum is the most cost-effective mining method for controlling surface subsidence.

## Control mechanism of partial filling-partial caving in multi-working face coordinated mining based on main key stratum

Practice and theoretical researche are both shown that the surface subsidence generated by coal mining does not completely conform to the random medium theoretical model of granular medium, and is closely related to the structural characteristics and lithology of the overlying strata. In particular, when the overlying strata contains multiple strong and thicker strata, the movement of the overlying strata will be divided into multiple strata movement groups, causing the overlying strata and the surface movement and deformation to show its own obvious particularity. To explain the mechanical behavior of hard stratum, researchers have successively proposed the key stratum theory, the plate theory and the bearing layer theory.

The super-thick weak cementation overburden in Yingpanhao Coal Mine contains two layers of thick sandstone, but the strata is soft in lithology, and its movement law is different from ordinary soft strata and hard strata. The existing mechanical theory cannot fully explain its movement mechanism. Even so, Figure 5 (c) shows that the double-layer thick sandstone has obvious control effect on the overburden movement. The key stratum theory can be used to explain its movement mechanism to a certain extent. Although partial filling-partial caving in multi-working face coordinated mining based on main key stratum is similar to the method of deep wide-strip mining, there is the essential difference between the bearing mechanism of the large-width isolation coal pillar and the composite support (filling body and section coal pillar). Figure 9 shows the control mechanism of partial filling-partial caving in multi-working face coordinated mining based on main key stratum.

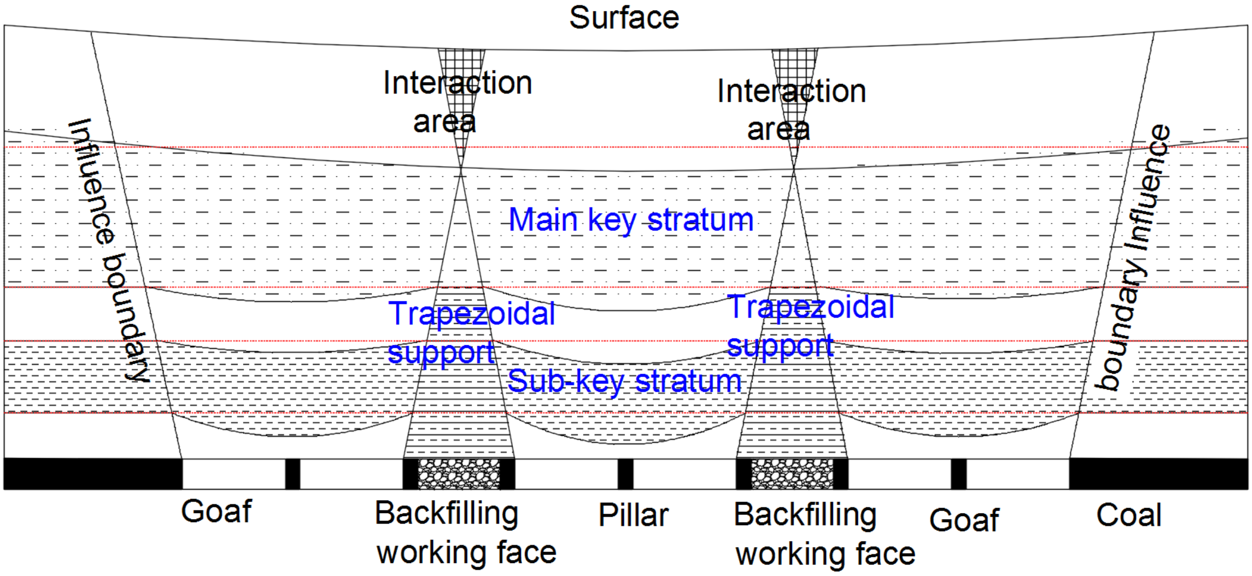


*Fig. 9 - Schematic diagram of control mechanism of partial filling-partial caving* in multi-working face *coordinated mining based on main key stratum structure*

In partial filling-partial caving in multi-working face coordinated mining based on main key stratum, the composite support and main key strata (main key strata and sub key strata) forms a dual control system of coordinated deformation, which step by step realizes the control of the movement of the overlying strata: The sub-key strata is close to the coal seam, which directly limits the damage height of the overlying strata and reduces the effective sinking space for upward transmission. The chief key stratum limits the upward transmission of the wave-shaped sinking basin, causing the overlying stratum to be a single gently sinking basin. The detailed cooperative control mechanism is as follows:

When the partial filling-partial caving in multi-working face coordinated mining based on main key stratum is completed, the goaf, formed by the double caving working face, loses the support of the coal body, and the overburden damage height develops to the bottom of the main key stratum. Due to the large size of the working face, although the overburden strata on the filling working face are supported by filling bodies, the overburden strata also have a damage in a certain degree. And, due to the limitation of the sub-critical strata, the overburden failure height only developed to the middle and lower parts of the sub-critical strata. The filling working face and caving working face of the mining area are arranged periodically to make the section of the overlying strata form a multi-peak hole structure. The filling working face and the strata above it form a trapezoidal support to separate adjacent goaf. Multiple trapezoidal supports jointly support the main key stratum and can continue to bear the load of the overlying strata. Under the action of its own flexural rigidity and inverted trapezoidal support, the sub-key stratum effectively blocks the upward transmission of the sinking space and diminishes the movement space of the overlying strata. Under the combined action of its own flexural rigidity and the trapezoidal support, the main key stratum further reduces the sinking amplitude, and the wave-shaped sinking trend is blocked or absorbed by the main key stratum when it is transmitted upward.

Judging from the simulation results of similar materials in Ref. 34, when single working face mining or even two-woking face was mined, the sub-critical stratum will block a large amount of effective subsidence space in its lower caving zone and fractured zone, which greatly reduces the sinking space of the overlying strata. From the numerical simulation results in Fig. 11(c), the multimodal pore failure structure is the stress transfer path inside the overburden. The main critical stratum itself and the overlying strata load transfer the stress to the trapezoidal support through the multimodal pore structure. Finally, it acts on the composite support of the filling working face and the section coal pillars, thereby forming multiple stress arches to support the overlying strata together.

## CONCLUSION

From the investigation of energy-polling evolution law of the super-thick weak cementation overburden in deep mining, this work proposes an approach for the control of regional strata movement and energy-polling of the super-thick weak cementation overburden, and compares the control effect with other mining methods. Results confirms the superiority of the partial filling-partial caving in multi-working face coordinated mining based on main key stratum and reveals its control mechanism. The following findings are attained：

(1) According to the elastic energy theory, the energy-polling evolution law of super-thick weak cementation overburden in deep mining is analyzed. The maximum energy-polling occurs on both sides of the goaf or on the section coal pillars, and the maximum energy-polling increases parabolically with the mining width.

(2) In the partial filling-partial caving in multi-working face coordinated mining based on main key stratum, the stress distribution of the composite filling body is parabolic, with high on both sides and low in the middle. The inside coal pillars of the backfilling working face has a greater stress concentration.

(3) Numerical simulation methods are employed to investigate the control effects of strata movement and energy-polling in mining methods such as full caving mining, full backfill mining, wide strip mining, and mixed backfill mining. From the reduction effect of surface subsidence, it follows: wide strip mining>full filling mining>large mining width-wide retention width>mixed backfill mining>partial filling-partial caving in multi-working face coordinated mining based on main key stratum >full caving mining. From the energy-polling control effect, it has the following effect: wide strip mining> large mining width-wide retention width >full backfill mining=mixed backfill mining> partial filling-partial caving in multi-working face coordinated mining based on main key stratum>full caving mining. With comprehensive consideration, the partial filling-partial caving in multi-working face coordinated mining based on main key stratum is the most cost-effective.

(4) In the partial filling-partial caving in multi-working face coordinated mining based on main key stratum, a dual control system of coordinated deformation was generated by the composite support and main key strata (main key strata and sub key strata), step-by-step achieving the control of the overlying strata movement. The sub-key stratum structure blocks the height of the overburden damage and greatly reduces the effective space upward transmission. The main key stratum structure further reduces the effective space upward transmission, and absorbs the wave-shaped sinking trend of the overburden until it develops into a single and gentle sinking basin.

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