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ORIGINAL PAPER

Mining-induced off-layer space evolution law and gangue grouting filling control mechanism

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Abstract
Separation grouting filling technology is widely used in surface subsidence management because of its simple process and good overburden control effect, while the changing pattern of overburden off-layer space (OS) during the mining process plays a key role in the selection of grouting timing and rock control effect. In this paper, the law of OS development and the mechanism of rock movement control by gangue slurry filling is studied by combining numerical simulation and physically similar simulation experiments with the engineering background of the $3^{-1}801$ working face of Hongqinghe coal mine. The results of the study indicate that the OS undergoes a slow growth period, an accelerated expansion period, a slow decrease period, and an accelerated decay period during the development process. The change of OS is closely related to the form of key layer bending and sinking, and the change of key layer from V-type sinking to basin-type sinking during the mining process is the turning point when the OS starts to decay faster, and timely grouting and filling before the turning point can effectively control the key layer breaking and sinking, reduce the stress concentration, and the effect of rock layer sinking reduction is obvious. The research results of this paper have certain theoretical value and practical significance for the technical scheme design of OS grouting and gangue filling treatment.

Keywords Off-layer space · Rock movement · Grouting and filling · Physical model · Gangue solid waste treatment

Introduction

Differences in the lithology of the overlying rock layers during coal mining usually result in uneven sinking of the rock layers, thus creating a delamination between the layers. Especially when there is a rock layer with significantly higher hardness and a certain thickness in the overlying rock layer, i.e., the key layer, the lithology of the upper and lower rock layers differs greatly, making the OS usually concentrated below the key layer (Zhou et al. 2019). It is known from the theory of the key layer that the rock layer above it and the key layer have the characteristics of synchronous breakage; in order to avoid the rock layer breakage and sinking upward to the surface, filling the OS and controlling the key layer breakage become the key to prevent and control surface subsidence (Zhang et al. 2015; X.J. Zhu et al. 2019).

The coal resources mining process usually not only causes overburden damage caused by surface subsidence but is also often accompanied by a series of adverse consequences, such as environmental pollution caused by the accumulation of gangue on the surface. The gangue crushed to a certain size and water mixed with the preparation of the gangue filling slurry backfill to the OS to support the overlying rock layer not only can solve the mine gangue waste but also can effectively control the surface subsidence of one of the effective way (Gruszczynski et al. 2018; Ugurlu et al. 2021; Yan et al. 2019). The effect of off-layer grouting filling on controlling the displacement of overburden strata is decisively related to whether the gangue slurry can fill the OS timely and effectively to support the overburden strata. Therefore, it is of great guiding significance to study the OS variation law of overburden strata and the effect of gangue slurry filling on controlling overburden strata for off-layer grouting filling technology

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and gangue solid waste treatment (Palchik 2020; Zhang et al. 2015).

For many years, the surface subsidence caused by mining has been of great concern to scholars worldwide, and the understanding of mining overburden separation as an important phenomenon in the process of mining subsidence has been gradually deepened along with the research on the surface subsidence problem (Chen et al. 2016; Donnelly et al. 2001). Mining subsidence began to be noticed in the 15th and 16th centuries, but the mechanism of its destruction was not studied in depth (Bell et al. 2000; Sheorey et al. 2000). With the continuous improvement of the theory of mining subsidence, the fact that the phenomenon of off-layer exists in the process of mining overburden damage was only revealed (Ren et al. 2022), and the German scholar H. Kratzsch first introduced the phenomenon of off-layer in his book "Mining Subsidence Engineering" in 1983 (H.Kratzsch 1983), after which the American scholar Syd S. Peng and Russian scholar B.JI. CamapHH further researched the formation and location of OS (Finfinger et al. 2017; Luo et al. 2000; Peng et al. 2019), and the proposed theory of equilibrium of mining overburden arch beam formed the prototype of the research on the distribution law of OS (Qian 2000; Xu and Qian 2000).

Since the impact of mining on the overlying strata is usually large scale and difficult to observe globally (W. Zhu et al. 2018), which makes the study of OS very difficult, scholars worldwide have proposed various theories and hypotheses to explain the process of generation, evolution, and disappearance of OS. The hinged rock block hypothesis proposed by the former Soviet Union scholar Kuznetsov for the first time expounded the stratification of the damaged rock mass (Kuznetsov et al. 2007). The theory of masonry beam and key layer constructed the theoretical framework for the study of OS (Kuznetsov et al. 2012; Qian et al. 1994). On this basis, numerical simulation, physical similarity simulation, mechanical derivation, and many other research tools are used to make the study of OS more detailed and specific. The temporal and spatial evolution law, influencing factors, and prediction models of OS in different geological conditions have become the focus of scholars and have achieved fruitful results in the development characteristics, distribution range, and model construction of OS (Fan et al. 2022; Yuan et al. 2019).

In summary, most of the current research on the OS is based on the passive understanding of the mining subsidence law, and the characteristics of the off-layer are studied from the perspective of overburden damage. Off-layer grouting is an active control technology for mining subsidence, but there are few studies on the cooperation between the development of OS and off-layer grouting technology from this perspective, especially the lack of research on the nonlinear variation law, causes, and grouting filling timing of OS size in the mining process.

This paper is based on the engineering background of gangue slurry filling in the overburden detachment zone of 3^{-1}801 working face of the Hongqinghe coal mine in the Inner Mongolia Autonomous Region. Numerical simulation and physical similarity simulation are used to study the variation law of the OS under the key layer in the Hongqinghe coal mine and to obtain the appropriate timing of OS grouting and its effect on the control of deformation of the key layer. The research results of this paper are of great significance to the control of surface settlement and disposal of gangue solid waste by off-layer slurry filling.

Engineering background

General situation of mine

The Hongqinghe coal mine is located in the Inner Mongolia Autonomous Region of China, with a production capacity of 8 million t/a. As shown in Fig. 1, the average mining thickness of the main mining 3^{-1} coal is 5.7 m, and the dip angle of the coal seam is 1~7°. The average buried depth of 3^{-1}801 working face is 659 m. At about 57 m above the coal seam, it is a hard, medium-grained sandstone with a thickness of 41.3 m, which is one of the key layers.

At the same time, Hongqinghe Coal Mine also faces the problem of gangue treatment in most mining areas. The annual gangue discharge is 600,000 tons. In order to effectively control a series of risks such as surface subsidence and dynamic disasters induced by the fracture of the key layer and make full use of the accumulated gangue on the surface, the off-layer filling technology of gangue slurry is proposed.

Grouting filling technology of gangue in OS

As an active surface subsidence reduction technique, off-layer grout filling is achieved by drilling from the surface into the OS and injecting the filling material into it using pipelines and high-pressure grout pumps. The high-pressure slurry will play a supporting role in the upper rock mass of the off-layer and compact the caving zone and fracture zone caused by coal seam mining in the lower part, forming a structure of filling body, rock mass, and coal pillar to support the overburden rock so as to reduce the surface subsidence, protect the aquifer, and prevent and control the rock burst (Jirina et al. 2010; Pal et al. 2020). The gangue slurry preparation station is arranged near the grouting filling borehole, and the gangue of the gangue hill is broken and sieved into different particle size filling raw gangue by a jib crusher, a roller sand making machine, a ball mill, etc. and mixed with water according to a certain ratio and concentration to

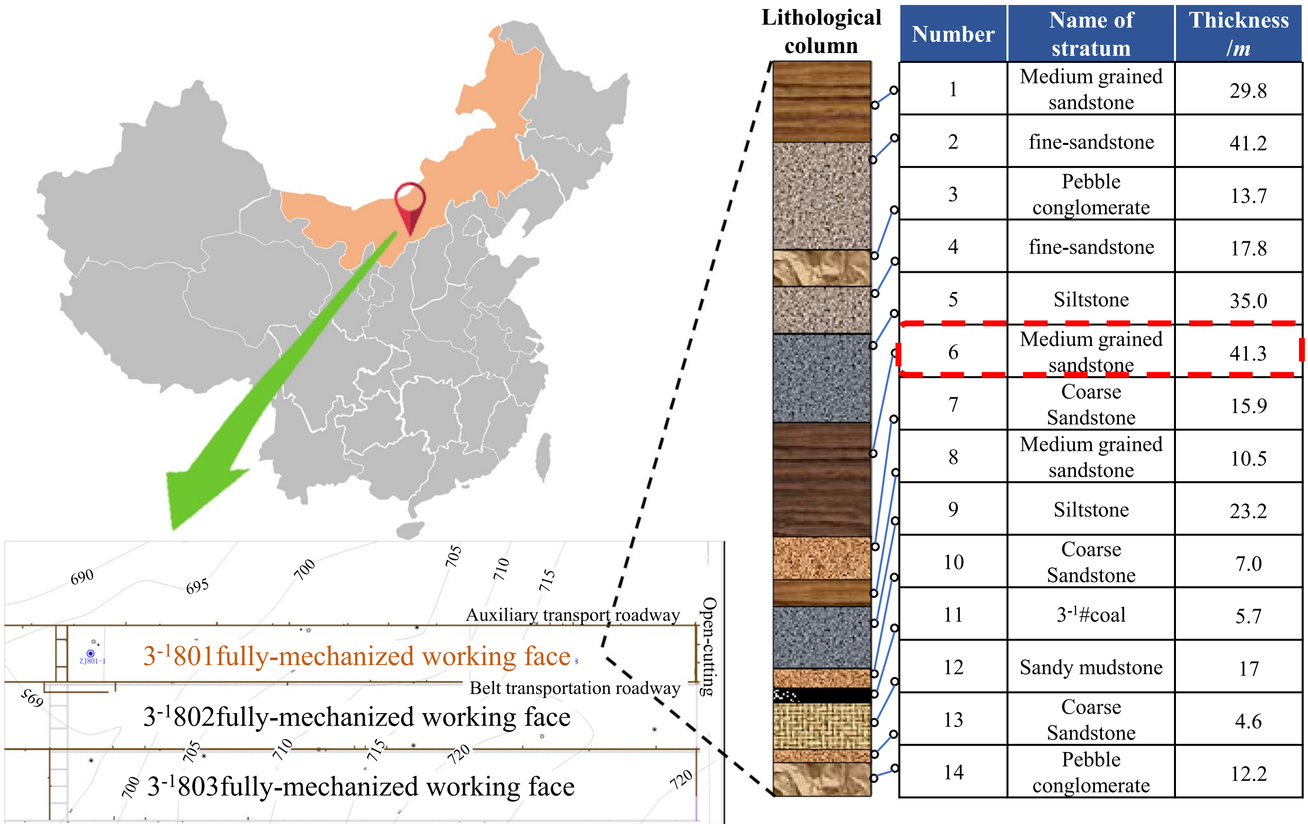

Fig. 1 Basic situation of Hongqinghe Coal Mine

prepare a pure gangue grouting filling material with good conveying performance (Fig. 2).

Numerical simulation of OS

Simulation scheme and off-layer void extraction

It is reasonable and feasible to use UDEC numerical simulations based on the discrete element method for studies that are not easy to monitor in practice, such as OS variations (Israelsson 1996; Poulsen et al. 2018). In order to study the development process of the OS, a two-dimensional model of coal-bearing strata in the strike direction of $3^{-1}801$ working face was established based on the engineering background of Hongqinghe Coal Mine. The length × height of the model is 600 × 270.5 m. According to the actual formation thickness and sequence, a total of 14 layers are established. The unbuilt rock above is equivalent to a 10.6 MPa uniform load, and 80 m coal pillars are reserved on both sides. The Mohr-Coulomb model is used for the failure criterion of coal and rock mass, and the Coulomb slip model based on joint area contact is used for the mechanical behavior of contact between rock blocks. The mechanical parameters of coal rock mass and the mechanical parameters of coal rock joint surface are shown in Table 1 and Table 2, and the model is shown in Fig. 3.

After the model reaches initial equilibrium, each excavation is 20 m and calculated to reach equilibrium until mining is completed. The displacement measuring line is arranged in the middle of the key layer to extract the subsidence curve of the key layer after each excavation balance. The original images of rock damage after each excavation in UDEC were exported and post-processed, and the OS was calculated using the open-source image processing software ImageJ. Firstly, the original image is imported and size corrected, the corrected original image is converted into a grayscale image, and the OS is identified by adjusting the grayscale range, and then the extracted OS area is calculated to obtain the change law of OS during the propulsion process, as shown in Fig. 4.

Analysis of simulation results

In order to compare and analyze the subsidence change of the key layer in the process of advancing, the bending subsidence curves of the key layer in each equilibrium stage of the model are combined, and the results are shown in Fig. 5. From the figure, we can see that the key layer can be

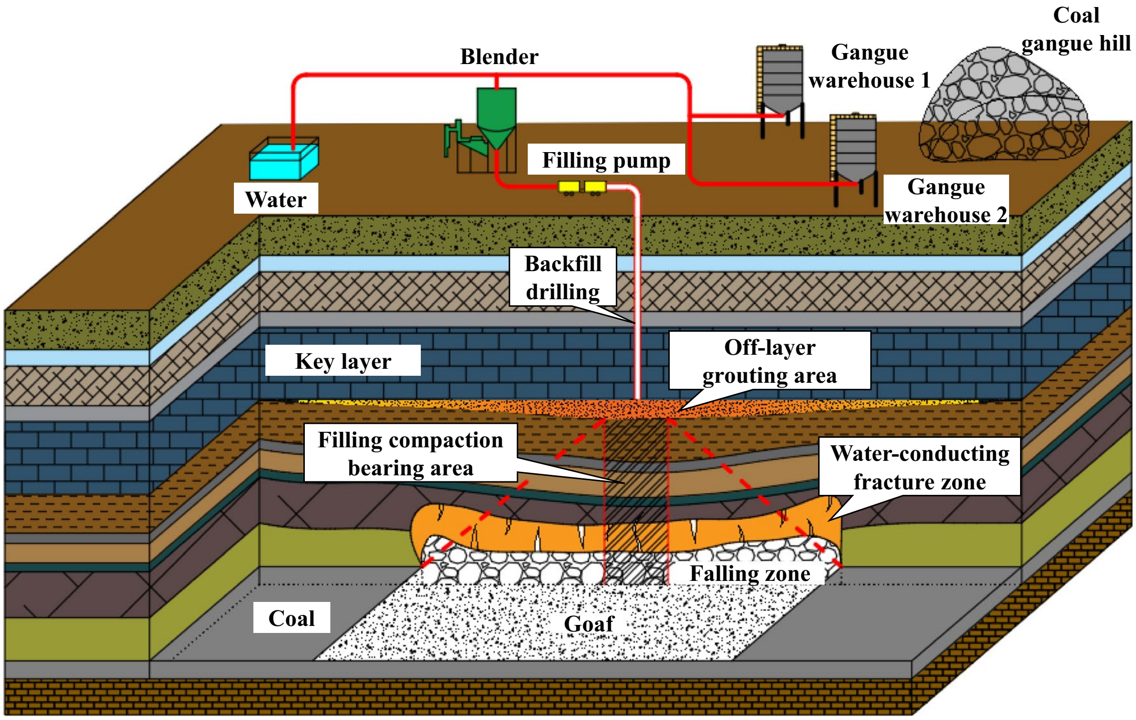

Fig. 2 Grouting filling principle of gangue in OS

Table 1 Mechanical parameters of coal rock

Number	Lithology	Density (g·cm^{-3})	Bulk modulus (GPa)	Shear modulus (GPa)	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (f °)
1	Medium-grained sandstone	2.59	5.70	4.70	1.40	3.40	37
2	Fine sandstone	2.61	4.20	3.80	1.80	3.10	38
3	Pebble conglomerate	2.56	5.90	4.90	1.50	3.40	39
4	Fine sandstone	2.61	4.20	3.80	1.80	3.10	38
5	Siltstone	2.35	6.70	4.70	1.90	3.50	42
6	Medium-grained sandstone	2.71	9.60	5.50	2.10	3.60	42
7	Coarse sandstone	2.38	4.80	2.70	1.10	3.70	35
8	Medium-grained sandstone	2.59	5.70	4.70	1.40	3.40	37
9	Siltstone	2.35	6.70	4.70	1.90	3.50	42
10	Coarse sandstone	2.38	2.80	2.00	1.80	3.20	38
11	3#coal	1.46	0.90	0.70	0.80	1.50	30
12	Sandy mudstone	2.10	2.30	2.90	1.00	2.20	35
13	Coarse sandstone	2.38	2.80	2.00	1.80	3.20	38
14	Pebble conglomerate	2.56	5.90	4.90	1.50	3.40	39

basically divided into four forms during the advancement process, namely, the small deformation stage, the V-type sinking stage with the largest sinking volume in the middle, the sinking form transformation stage, and the basin-type sinking stage.

In the small deformation stage, the working face advances a short distance, the rock damage is not developed upward to the key layer for the time being, and the key layer is basically not bent down. In the V-type sinking stage, the maximum settlement is in the middle of the direction of the key layer, and the maximum settlement gradually increases with the increase of the advancing distance, and the increasing speed shows the obvious characteristics of "slow-fast-slow." When the maximum sinkage of the key layer reaches about 4.3 m,

Table 2 Coal rock joint surface parameters

Number	Lithology	Normal stiffness (GPa)	Tangential stiffness (GPa)	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (f °)
1	Medium-grained sandstone	4.20	2.39	0.21	0.21	24
2	Fine sandstone	4.10	2.49	0.21	0.22	23
3	Pebble conglomerate	4.00	2.29	0.21	0.20	24
4	Fine sandstone	4.30	2.69	0.21	0.22	24
5	Siltstone	4.60	1.58	0.69	0.68	23
6	Medium-grained sandstone	4.80	2.70	0.69	0.36	22
7	Coarse sandstone	1.30	0.90	0.69	0.62	23
8	Medium-grained sandstone	1.50	0.95	0.69	0.68	23
9	Siltstone	1.30	0.90	0.69	0.62	20
10	Coarse sandstone	1.30	0.90	0.61	0.92	20
11	3#coal	1.10	0.58	0.21	0.09	20
12	Sandy mudstone	1.50	0.95	0.21	0.62	20
13	Coarse sandstone	4.30	2.60	0.21	0.22	10
14	Pebble conglomerate	3.80	1.28	0.19	0.21	17

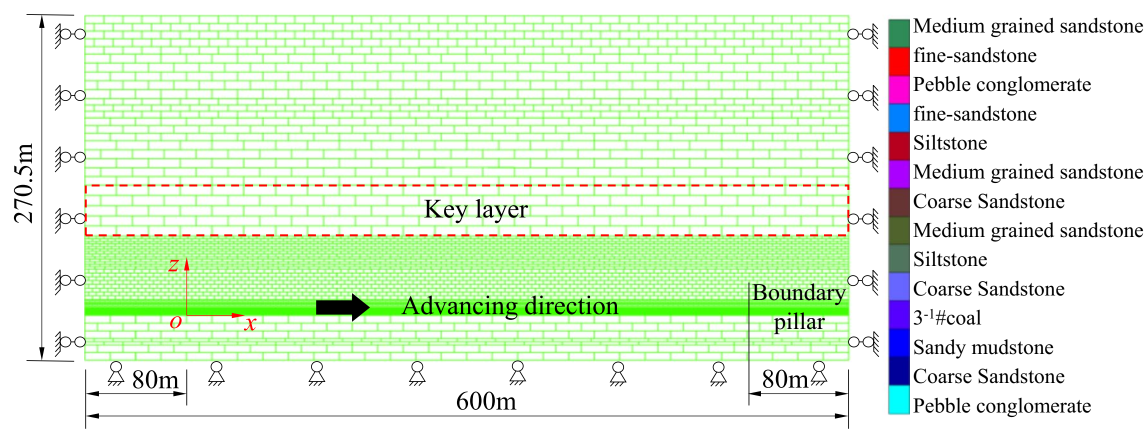

Fig. 3 Establishment of UDEC numerical model

the V-type sinking basically ends, and the central key layer gradually transitions from V-type sinking to basin-type sinking in the form of rotary deformation on the side close to the coal wall with the side of the open cut as the axis.

The relationship between the OS and the advancing distance is obtained by extracting the area of the separation gap under the key layer during the advancing process, as shown in Fig. 6. In the small deformation stage of the key layer, the OS increases slowly with the increase of the advancing distance. In the early stage of the V-type sinking stage of the key layer, with the increase of the advancing distance, the area of the OS shows a rapid upward trend. In the middle and later stages, the speed slows down and the OS begins to decrease slowly. The change of the OS area is relatively small during the transition period from the V-type sinking stage to the basin-type subsidence. When entering the basin-type subsidence, the OS area enters the accelerated attenuation stage. In order to control the key layer before the OS attenuation caused by the large settlement of the key layer and inject the gangue filling slurry as much as possible, the grouting timing is effective between the rapid increase of the OS and the slow decrease stage.

Physical similarity simulation design of gangue grouting filling in OS

Simulation scheme and test materials

In order to better guide the off-layer grouting filling, according to the geological conditions of 3^{-1}801 working face in Hongqinghe Coal Mine, two two-dimensional plane models

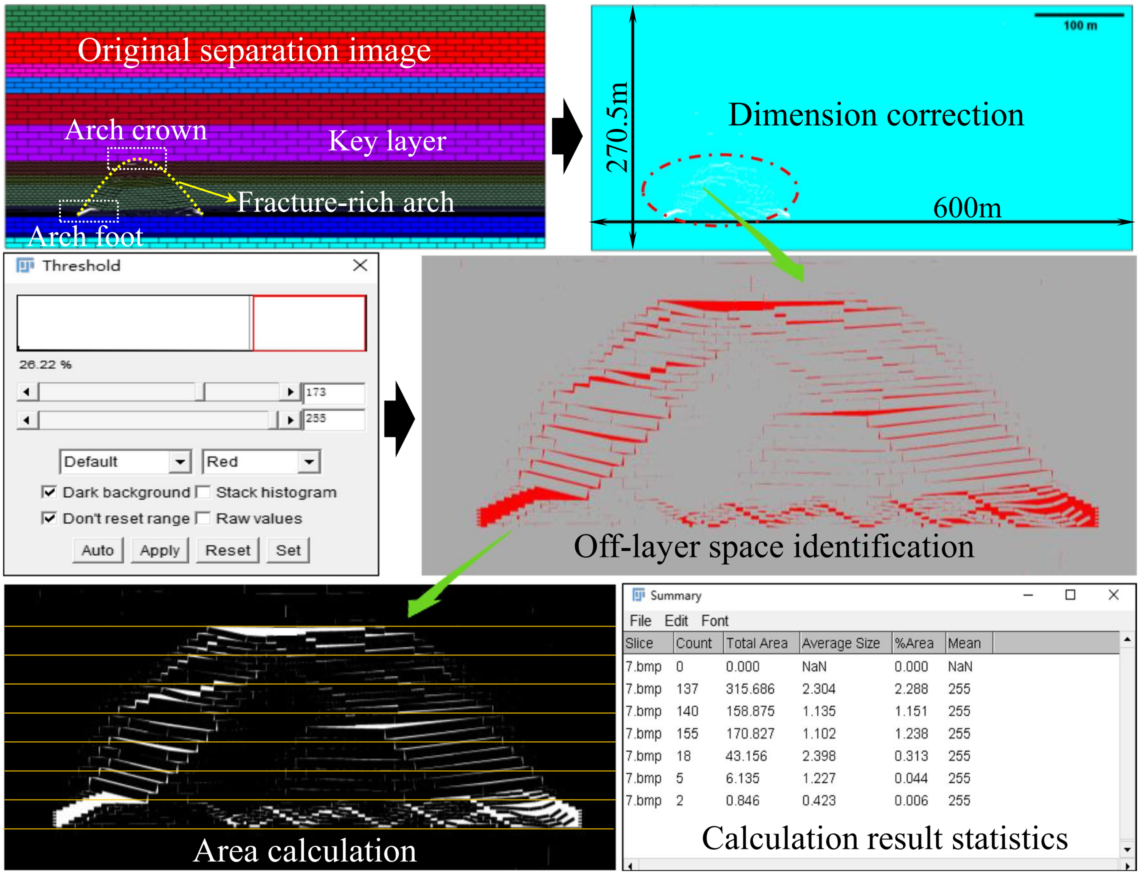

Fig. 4 Post-processing process of simulation results

with length, width, and height of 2.5m×0.3m×1.38m were established by using river sand, calcium carbonate, gypsum, and water. The model includes 3^{-1} coal seam, 3 floors, and 10 overlying strata. Limited by the experimental conditions of the model height, the load applied by the overlying strata above the 10 layers is converted by the pressure device. The simulated geological mining conditions are as follows: The advancing length of the working face is 280 m, 110 m wide boundary coal pillars are set on both sides, the mining height is 5.7 m, and the buried depth is 659.7 m. According to the similarity criteria, the basic parameters of the physical model are shown in Table 3.

According to the 3^{-1}801 working face borehole histogram shown in Fig. 1, the mechanical properties of each test stratum and the simulation experience of worldwide scholars (Ghabraie et al. 2015; G. Li et al. 2020; H.C. Li 1988) and the material ratio parameters of the similarity simulation test are determined, as shown in Table 4.

The simulated grouting filling material used in the test was prepared by gangue from Hongqinghe Coal Mine and tap water. The gangue was crushed and sieved into fine powder gangue (particle size less than 0.15 mm) and large particle gangue (particle size of 0.15~1 mm) by jaw crusher, roller sanding machine, and ball mill. By measuring the sedimentation rate and expansion degree of gangue slurry with different ratios and different concentrations, the gangue filling slurry with good transportation performance with a mass ratio of coarse and fine gangue of 1:1 and a mass concentration of 65% was prepared. The specific preparation process is shown in Fig. 7.

Model laying and monitoring scheme

The laying process of the model is shown in Fig. 8. The model is laid layer by layer according to the order of the stratum from bottom to top. Firstly, the simulation materials of each rock layer shown in Table 4 are put into the mixer according to the proportion weight to fully mix, and then, the mixture is evenly spread in the model frame. The height of the layer is consistent with the design height by using the special hammer compaction. After the layer is paved, a layer of mica sheet less than 1 mm is evenly spread so that the cycle until the design model height. Model 1 was mined using the caving method, and when laid down to the medium-grained sandstone of the key layer, formation 6, five strain gauges were buried in Formation 6 at the interval

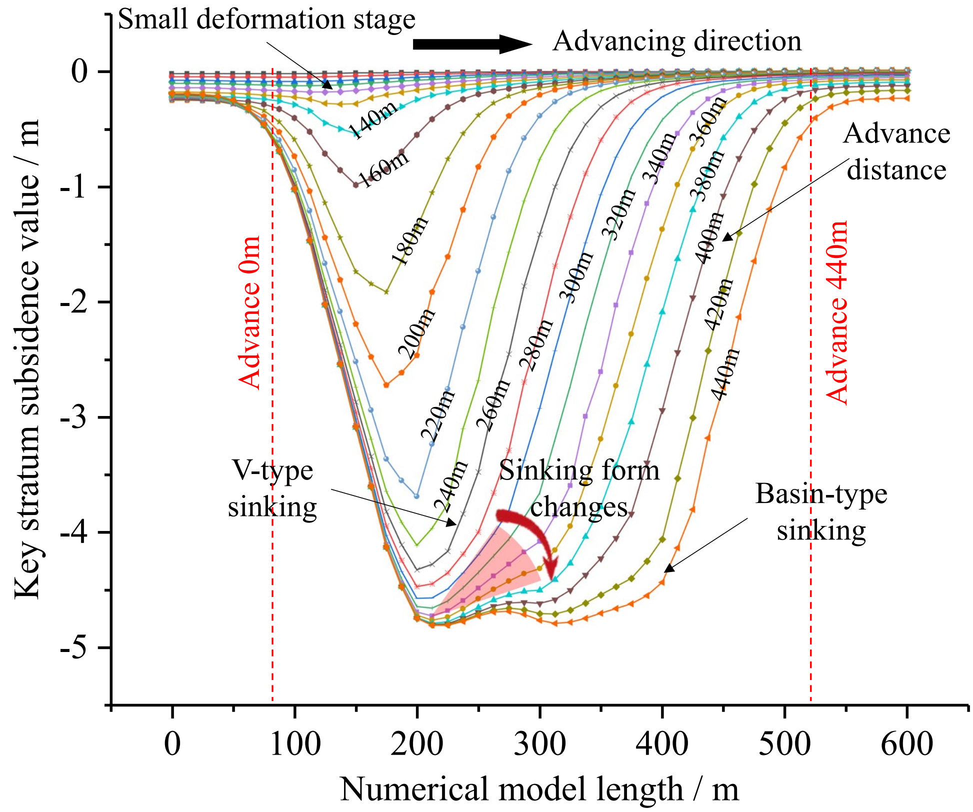

Fig. 5 Key layer bending subsidence curve

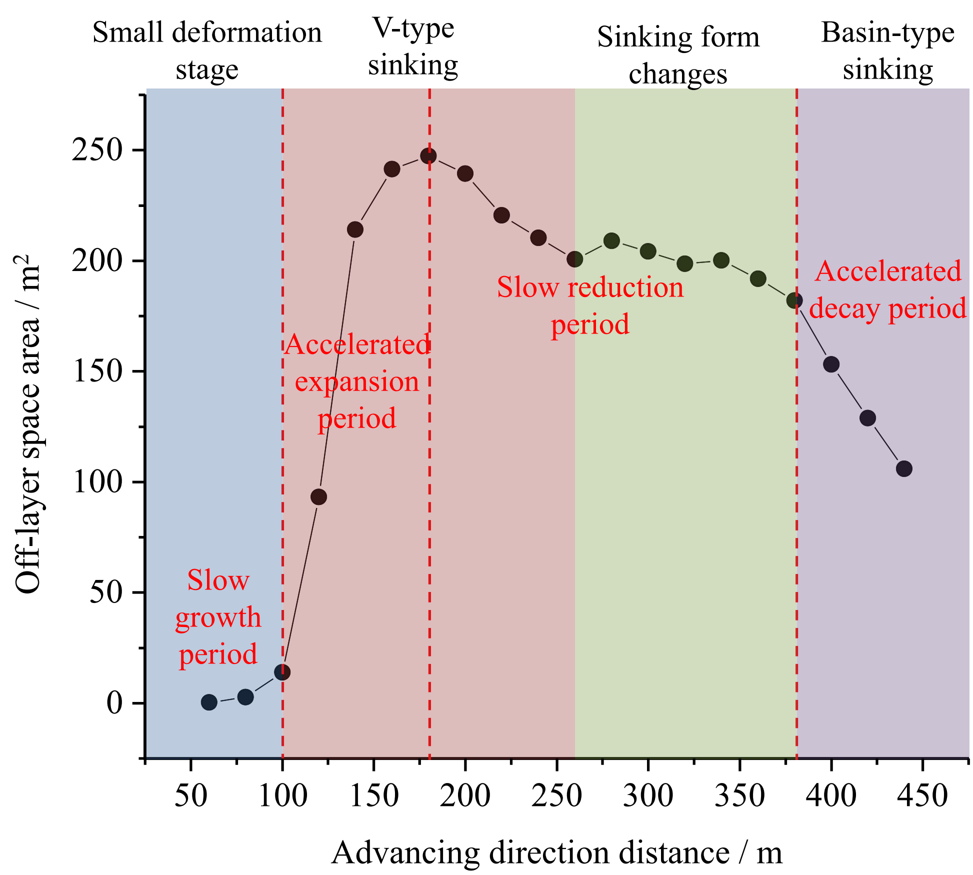

Fig. 6 Diagram of the relationship between OS and advancing distance

Table 3 Basic parameters of physical similarity simulation

Item	Parameter	Item	Parameter
Model type	2D plane	Excavation height	2.85 cm
Model length	250 cm	Excavation distance	140 cm
Model width	30 cm	Excavation steps	44
Model height	138 cm	Unilateral model boundary	55 cm
Coal seam height	2.85 cm	Single excavation length	3.2cm
Geometrical ratio	200:1	Excavation interval	0.5h
Volume-weight ratio	1.667:1	Cumulative excavation time	22h
Stress ratio	333.4:1	Overlying load	31.7kPa

distances shown in Fig. 8. On the basis of the research of model 1, the model 2 is designed to simulate the off-layer grouting filling under the key layer by using the grouting water bag. When the coarse-grained sandstone of the No. 7 rock layer is laid, the grouting filling bag with a length of 140 cm and the grouting pipe with a diameter of 0.5 cm is embedded in the middle position above it to simulate the off-layer grouting filling. The grouting pressure table is used to judge whether the OS is full, and the grouting is stopped when the grouting pressure begins to rise. The remaining steps of model 2 are the same as the laying process of model 1. After the model was naturally dried for 8 days, the mold was removed and white latex paint was brushed on its surface, and the speckles were evenly drawn with black pigments.

Table 4 Similarity simulation experiment material proportion parameters

Number	Lithology	Simulated thickness (cm)	Simulated strength (kPa)	Sand (kg)	Calcium carbonate (kg)	Gypsum (kg)	Water (kg)
1	Medium-grained sandstone	14.905	202	129.35	21.56	21.56	28.75
2	Fine sandstone	20.595	141	205.95	20.60	20.60	30.89
3	Pebble conglomerate	6.855	119	59.49	13.88	5.95	13.22
4	Fine sandstone	8.92	141	89.20	8.92	8.92	13.38
5	Siltstone	17.485	135	183.59	7.87	18.36	26.23
6	Medium-grained sandstone	20.64	202	179.13	29.85	29.85	39.81
7	Coarse sandstone	7.975	222	76.56	5.74	13.40	11.96
8	Medium-grained sandstone	5.25	202	45.56	7.59	7.59	10.13
9	Siltstone	11.62	135	122.01	5.23	12.20	17.43
10	Coarse sandstone	3.505	222	33.65	2.52	5.89	5.26
11	3#coal	2.85	90	27.36	4.79	2.05	4.28
12	Sandy mudstone	8.5	78	87.43	10.20	4.37	12.75
13	Coarse sandstone	2.315	222	22.22	1.67	3.89	3.47
14	Pebble conglomerate	6.11	119	53.03	12.37	5.30	11.78
Total		137.5		1314.5	152.8	159.9	229.33

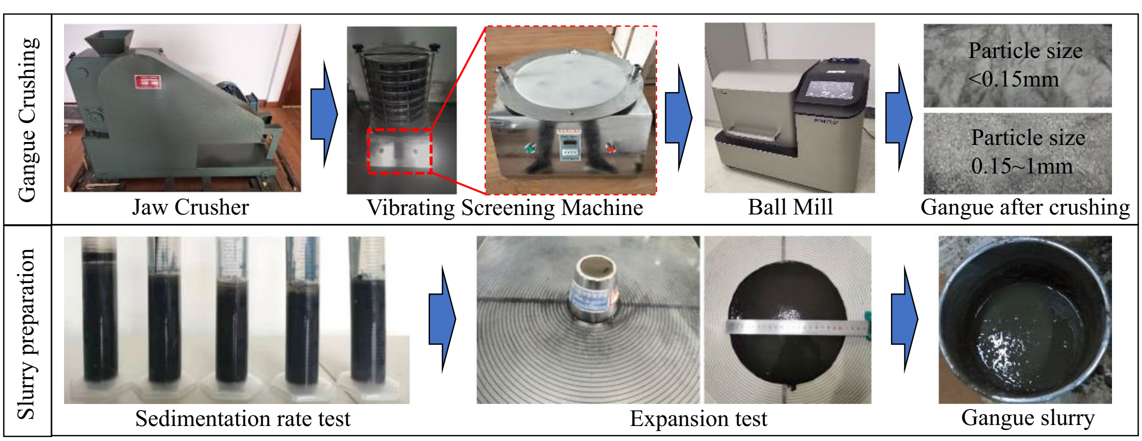

Fig. 7 Preparation process of gangue slurry

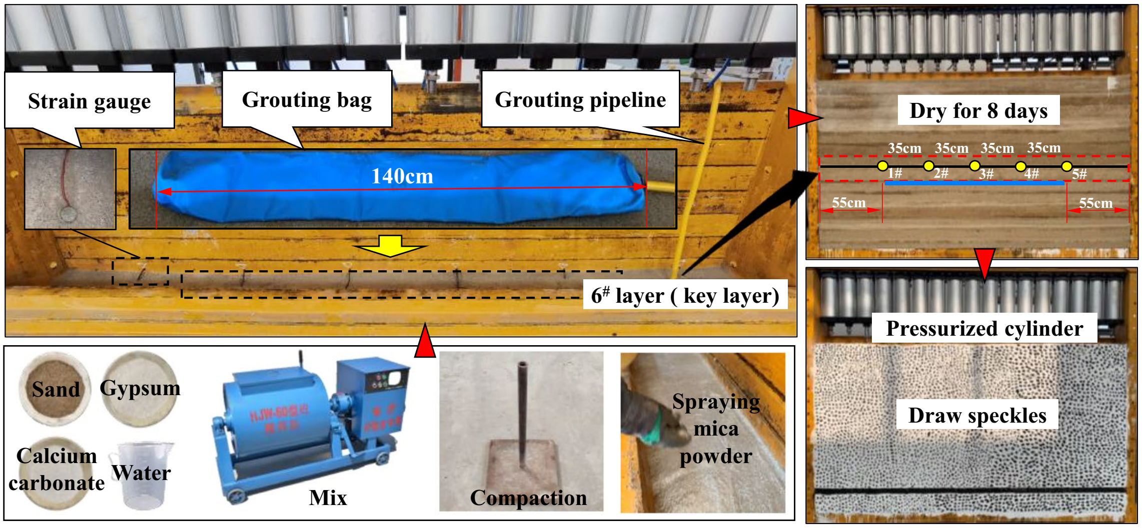

Fig. 8 Similar model laying process

Physical similarity simulation is mainly used to monitor the failure of the model, the displacement of rock strata, and the change of stress. The layout of the monitoring system is shown in Fig. 9. The strain gauge embedded in the rock layer is connected to the YBY-BZ2205C programmable static resistance strain gauge. The strain range is ±30,000 με, and the resolution is 1 με. The stress change of the model during mining is monitored. The MatchID-2D non-contact full-field strain measurement system is used for model displacement monitoring. The system uses a digital image correlation algorithm, including a 29 million pixels AVT industrial camera, optical lens, lighting system, supporting laptop, and MatchID-2D analysis software. The strain measurement range is 0.005~2000 %, and the accuracy is 10 με. The positions of speckle patterns in different images are permanently photographed by a fixed high-speed camera, and the deformation process of speckle patterns on the model surface is tracked. The grayscale changes in the speckle domain are calculated to provide two-dimensional visualization for experimental measurement of displacement and deformation.

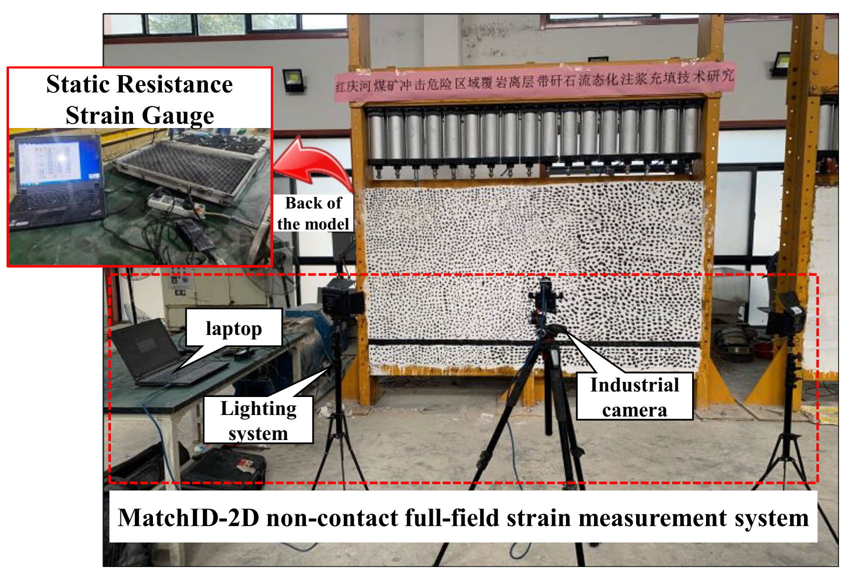

Fig. 9 Similar model monitoring system layout

Result and discussion

Evolution law of OS under key layer

In order to study the evolution and expansion law of OS under the key layer, the photos taken by a high-speed camera at different advanced distances of the caving mining model are calculated and processed, and the vertical displacement cloud diagram of overburden strata is obtained, as shown in Fig. 10.

As shown in Fig. 10a, when the working face is advanced to 144 m, the overlying strata have an obvious grouping breaking phenomenon, the broken rock layers are stacked into trapezoids, and there are small separations between the broken rock layers, while there is a large crescent separation space between the upper and unbroken rock layers. The length of the OS reaches 93 m, the maximum height in the middle is about 3.5 m, and the height from the coal seam is 41 m. At this time, there is no obvious sinking phenomenon in the key layer. The fracture angle of each rock stratum is basically the same as that of the coal seam, which is about 65~70°. The fracture angle of the rock stratum near the open-off cut side is slightly larger than that of the coal wall side of the working face.

According to Fig. 10b, when the working face advances to 227 m, the off-layer continues to develop upward, reaching the bottom of the thick and hard key layer, forming a relatively narrow separation space, about 164 m long, 56 m away from the coal seam height, and the formed OS has no obvious attenuation phenomenon. At this time, there is a long-distance suspension below the key layer, and there is a certain space for subsidence activity. However, due to the characteristics of hard overburden, there is no obvious subsidence displacement in the middle suspension.

The analysis of Fig. 10c revealed that when the working face advances to 258 m, the length of the OS under the key layer expands to 181 m in the strike direction with the advancement of the working face. The OS develops to the bottom of the key layer and does not develop upwards. The height of the off-layer remains at 56 m. In the direction of advancement, the rock strata in the middle of the key layer and its small range above have an overall subsidence phenomenon, causing the attenuation of the OS.

As seen in Fig. 10d, when the working face advances to 280 m, the length of the OS under the key layer increases to 229 m, but the key layer has already produced a large subsidence displacement at this time. This subsidence displacement gradually passes to the upper rock stratum. The subsidence phenomenon of the key layer in the middle of the strike direction of the working face is the most obvious, and the OS under it also decays rapidly.

In summary, from Fig. 10, it can be qualitatively analyzed that with the increase of the advancing distance, the height of the OS will temporarily stop upward development when it develops below the key layer without filling treatment,

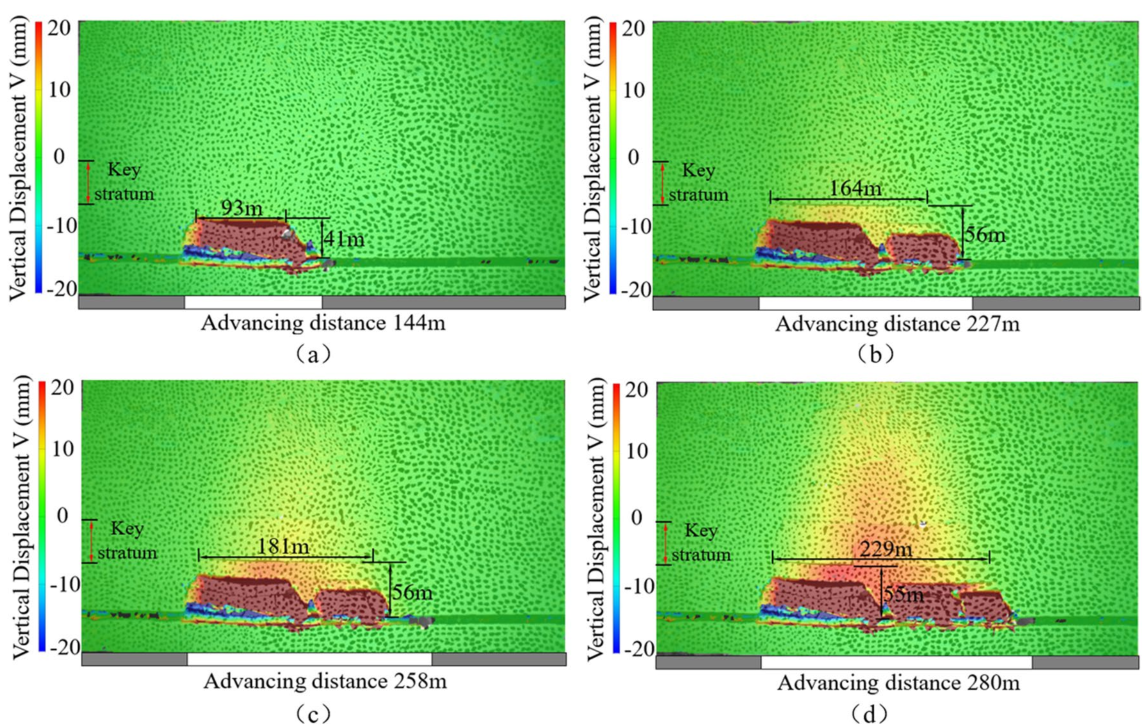

Fig. 10 Vertical displacement cloud diagram of overburden rock in caving mining

and the length of the off-layer will increase with the increase of the advancing distance. In the direction of the working face, the OS under the key layer shows the characteristics of increasing first and then decreasing gradually with the sinking of the key layer. In order to accurately analyze the displacement of the key layer in the process of working face advancing, the horizontal survey line is taken at the middle position of the key layer in the vertical displacement cloud map of the overlying rock in the caving method, and the subsidence displacement curve of the key layer at different advancing distances is extracted, as shown in Fig. 11.

According to Fig. 11, the key layer subsidence curve obtained by the physical similarity simulation test is similar to the key layer bending subsidence curve obtained by numerical calculation (Fig. 5) in terms of morphological changes. However, due to the lack of photo recording accuracy of the physical similarity simulation test, the curve transformation process is not continuous, but the subsidence curve of the key layer in the process of advancing can still be clearly classified, that is, small deformation stage, V-type sinking, sinking form change stage, and basin-type sinking.

In the small deformation stage, the maximum subsidence of the key layer of the model is about 1.0 mm, which is converted into the actual subsidence of about 0.2 m, and the corresponding OS is in a slow growth period. At the end of the V-type sinking stage, the maximum subsidence of the key layer increases to 2.3 m. The position of the key layer near the side of the open-off cut remains basically unchanged during the conversion of the subsidence form. The key layer rotates in the form of one end hinged and one end sinking and moving. In the process, the OS, from the rapid development to the maximum, began to turn to slow attenuation. During the whole test process, the maximum subsidence of the key layer mined by the caving method is 2.65 m, and the maximum subsidence displacement appears on the side of the key layer near the coal wall. When the working face continues to advance, it can be inferred that the key layer will be near the coal wall side of the working face. Fracture failure occurs, resulting in rapid attenuation of OS and transmission of mining influence to the ground.

Control of key strata by separation grouting

Through the above analysis, it can be seen that if Hongqinghe Coal Mine does not carry out filling treatment after mining, with the advancement of the working face, the OS will first temporarily develop below the key layer and then continue to expand along the direction of the working face, resulting in a gradual increase in the suspended area of the key layer. When the critical span is reached, the key layer begins to break on the side of the open-off cut and the side of the coal wall, accompanied by a certain degree of rotary deformation, resulting in the attenuation of the OS formed below. It can be seen from the above research that it is a suitable time to carry out off-layer grouting before the middle and late stages of the V-type sinking stage of the key layer to the basin-type sinking stage. During the test, it is observed that the initial off-layer grouting is carried out when the OS under the key layer is accelerated. The horizontal survey line is arranged in the middle of the key layer of the vertical displacement cloud map of the overburden of the off-layer grouting filling model, and the subsidence displacement curve of the key layer at different advancing distances is extracted, as shown in Fig. 12.

As shown in Fig. 12, in the small deformation stage of the key layer and the early and middle stage of the V-type sinking stage of the key layer, the subsidence curve is basically consistent with the non-grouted filling model. After the first

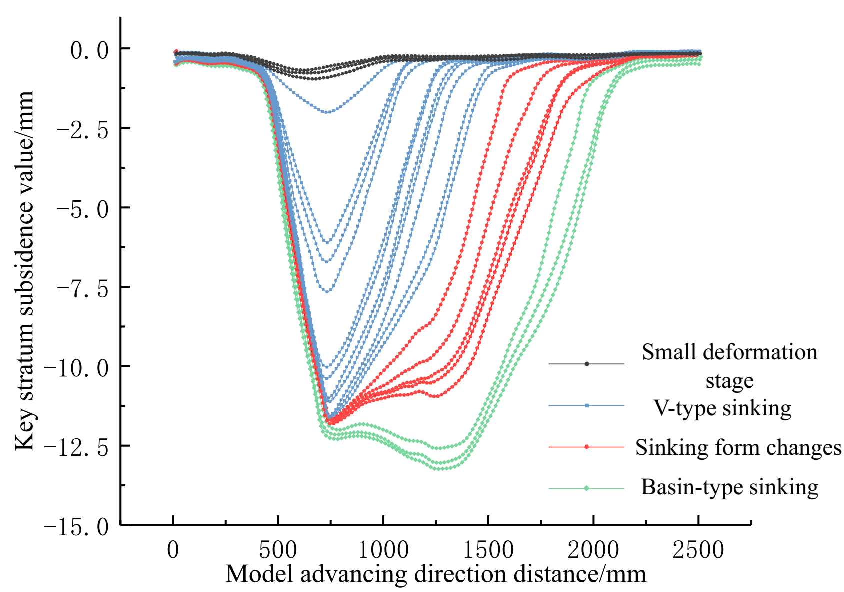

Fig. 11 Key strata subsidence curve of caving mining

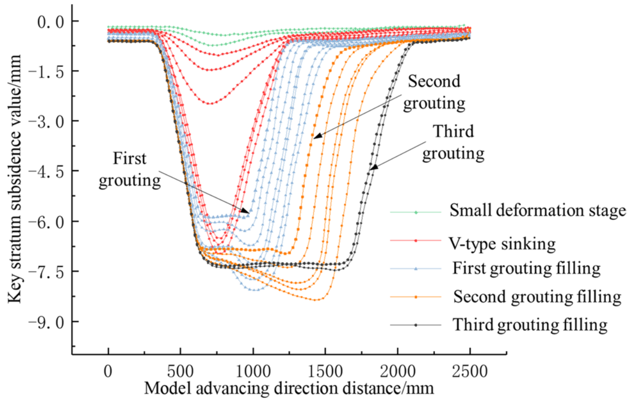

Fig. 12 Grouting filling key layer subsidence curve

off-layer grouting filling, the maximum subsidence value of the key layer is reduced from 1.41 to 1.17 m. It can be seen that the filling slurry reduces the bending amount of the key layer to a certain extent after injecting the OS. After the first filling, as the advancing distance continues to increase, the maximum subsidence value of the key layer increases slowly and gradually exceeds that before filling, reaching 1.62 m. In this process, a new OS will continue to be formed. The key layer near the coal wall is located above the newly formed OS, and the sinking speed is fast and the sinking form is U-shaped. The key layer near the open-off cut side sinks slowly and almost horizontally due to the accumulation and support of solid materials in the gangue grouting material, which is obviously different from the way of the inclined sinking of the whole key layer without filling.

After the second off-layer grouting filling, it can be seen that the key layer is restored from the inclined subsidence state to the basin-like subsidence state, and the maximum subsidence value of the key layer is reduced to 1.40 m. After filling, the slurry diffuses to the newly formed OS under the action of pressure, which reduces the subsidence of the key layer on the side of the coal wall and makes the key layer in a relatively stable state. The third off-layer grouting filling effect is similar to the previous two.

In order to analyze the influence of off-layer grouting filling on the stress distribution of the key layer, the stress data of the key layer monitored by static resistance strain gauge during caving mining and grouting filling mining are shown in Fig. 13.

According to Fig. 13a, when the 1 # strain gauge is above the open-off cut, the stress is suddenly relieved from an average of 14.3 MPa when the excavation is just carried out, and then the stress increases first and then decreases with the advance of excavation. Finally, the average stress is stable and maintained at a horizontal state. The stress monitored by 2 # to 5 # strain gauges has the same trend. When it is not affected by mining, the stress is maintained at an average of about 14.3 MPa. With the advancement of the working face, the stress is affected by the advanced stress, and the stress rises to 21.5 MPa, 21.4 MPa, 20.1 MPa, and 20.9 MPa. When the mining of the working face exceeds the vertical distance of the strain gauge, the stress decreases and finally slowly reaches the equilibrium state.

As shown in Fig. 13b, when the mining distance of the working face exceeds the vertical distance of 1 # and 2 # strain gauges, the off-layer grouting filling has not been carried out. The trend of the front section of the stress curve is similar to that of the caving method, and the maximum stress reaches 19.5 MPa and 20.5 MPa, respectively. Before the 3 # strain gauge is affected by the advance stress, the grouting filling operation is carried out. It can be found that the peak stress caused by mining at 3 #, 4 #, and 5 # strain gauges is reduced to 16.6 MPa, 17.4 MPa, and 16.8 MPa, respectively. In the stress change curve from 1 # to 5 #, in addition to the stress change caused by mining influence, a small stress disturbance caused by

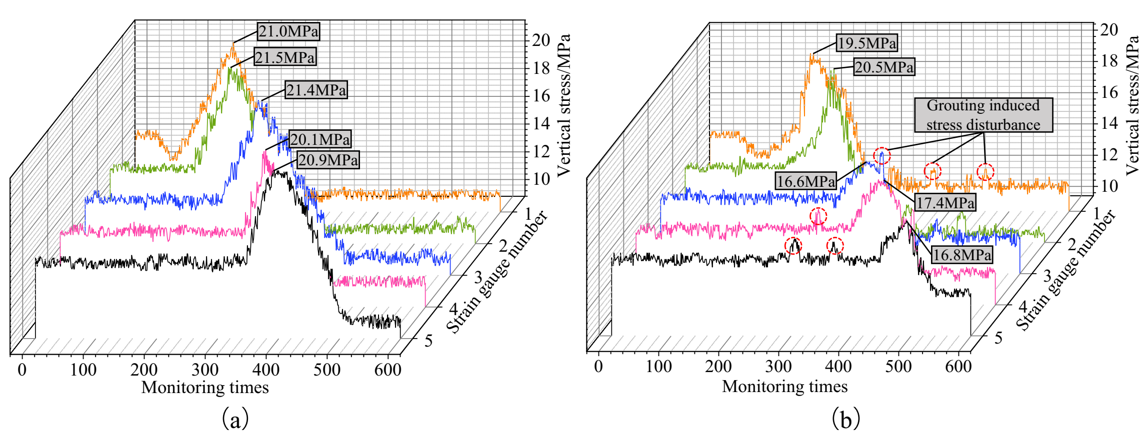

Fig. 13 Stress change curve of the model

grouting can also be found, but it does not have a great impact on the overall change trend.

In summary, timely off-layer grouting filling can inject as much gangue filling slurry as possible before the rapid attenuation of the OS, effectively reducing the rotary sinking of the key layer and inhibiting its breaking deformation. After grouting, the stress concentration of the key layer is effectively reduced, and the risk of strain energy accumulation and release is reduced.

Conclusions

(1) Through numerical simulation, the variation curve of the OS area and the bending subsidence curve of the key layer in the process of mining are extracted. It is concluded that the OS has experienced a slow growth period, an accelerated expansion period, a slow reduction period, and an accelerated attenuation period in the development process, while the bending subsidence curve of the key layer shows a small deformation stage, a V-type subsidence stage, a subsidence form conversion stage, and a basin subsidence stage. In the key layer in the V-type subsidence stage, the OS accelerated expansion in the early stage, and in the basin-type subsidence stage, the OS entered the accelerated attenuation period.

(2) Two similar physical simulation tests of caving mining and off-layer grouting filling mining are designed. When the off-layer develops below the key layer in caving mining, it does not develop upward with the advancement of mining, but expands horizontally in the direction of advancement. The bending and sinking form of the key layer is similar to that of numerical simulation. When the limit span step is reached, the damage is transmitted upward, causing the subsidence failure of the upper strata and causing the accelerated attenuation of the OS.

(3) In the middle and late stage of the V-type subsidence stage of the key layer to the basin-type subsidence stage, the OS is relatively large and the key layer has not broken down. During this stage, the timely off-layer grouting filling can effectively control the bending subsidence of the key layer and reduce the stress concentration caused by mining.

(4) Due to the limitation of two-dimensional physical similarity simulation test conditions, this paper can only make a conclusion on the bending and sinking law of the key layer in the direction of the strike direction and the variation law of the OS caused by it. Although it can guide the off-layer grouting filling technology to a certain extent in engineering, in order to more accurately reflect the actual situation, it is necessary to further study the OS change in the whole mining area in the future.

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Data Availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests The authors declare no competing interests.

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