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Research on reasonable mining scheme for coal recovery in thick coal seam under buildings and other structures

Due to overe xploitation in the last years, coal under buildings and other structures has become a significant resource to maintain the sustainability of coal mines in China. However, buildings and other structures above mining area are easily damaged caused by surface subsidence after mining. In order to recover coal under surface structures and ensure the stability of surface structures, the short-strip coal recovery with backfill method is proposed. By using a numerical simulation, this paper simulates the subsidence of overlying strata to select the mining sequence and the strip width. A reasonable mining sequence is determined and the strip width is primarily selected as 5m or 6m. Afterward a physical simulation is conducted to validate the numerical simulation. And the subsidence law of overlying strata during mining and filling is analyzed for the 5m-width and 6m-width strip respectively. Finally, the reasonable strip width is determined as 6m according to the surface subsidence and production efficiency. By employing the above mining scheme, the surface subsidence and deformation of two surface structures above the mining area of Sima coal mine is predicted, which shows the mining scheme can ensure the stability of two surface structures above mining area. The research results provide a reasonable and reliable reference for coal recovery in thick coal seam under buildings and other structures.

Keywords: *Coal recovery; thick coal seam; mining scheme; numerical simulation; physical simulation.*

1. Introduction

Coal is the main source of China's primary energy, but about 13.8 billion tonnes of coal is buried under buildings, railways, and water bodies which is almost three times of annual coal production of China [1]. Due to the predatory mining which preferentially focuses on simple structure coal seams, the remained coal under buildings and other structures becomes an important source to achieve sustainable production of coal mines with low mineable reserves, especially in the eastern coal mines and some old coal mines in China [2-4].

To recover coal under surface structures, various surface subsidence-control methods have been employed when mining coal under buildings and other structures. The subsidence-control methods mainly include two types: partial mining method with coal pillar as support system, including strip mining [5-7], room-pillar mining [8], et al and backfill mining method with backfill material as support system [9,10]. The backfill mining method consists of paste filling mining [11-17], solid dense wastes filling mining [18-22], high-water packing filling mining [23-25]. Strip mining is a widely applied partial mining method which divides a mining area into stripped shapes. One strip is mined with next strip maintained. The load of the overlying strata is supported by remaining coal pillar, and the surface movement and deformation are controlled in an allowing range. Strip mining is suitable for coal under buildings and other structures which needs strict requirement of surface deformation. However, coal resources are excessively wasted at a very low coal recovery ratio. The room-pillar mining also wastes coal resources due to the coal pillar. The backfill mining uses filling materials to fill the gob to control the subsidence of the overlying strata. Nevertheless, the disposable investment is great and the production efficiency is relatively low due to the restricting between mining and filling [22]. Most of the above subsidence-control methods are used for coal seams less than 5m [26], with little attention on thick coal seam, which accounts for nearly half of China's coal reserves. Sun et al [27] proposed short-strip coal pillar recovery with cemented paste backfill method, however it did not take into account the effect on surface structures. Conventional longwall mining is difficult to meet the requirement of subsidence control and economic performance: if strip mining method used, the recovery ratio is low and the waste of resources is great; if backfill mining method employed, the restricting between mining and filling is serious and the disposable investment is great.

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(a) House collapse (b) Road subsidence

Fig.1 House collapse and road subsidence in Sima Coal Mine of Luan Group [28]

In Luan Group, Shanxi province, China, the thickness of primary mineable coal is about 7m and the coal under buildings and other structures has reached 2.6 billion tonnes, accounting for 43.8% of coal reserves, which greatly shortens the service life if abandoning the coal under buildings and other structures [4]. The damage of buildings and other structures caused by surface subsidence after conventional mining are common in Luan Group such as house collapse is shown in Fig.1(a) and road subsidence in Fig.1(b).

To exploit the coal resource under buildings and other structures in Luan Group, the short-strip coal recovery with backfill is proposed. The basic practice is to divide a mining area into short stripped shapes and one short-strip is mined with next short-strip maintained. Then the excavated space is filled with backfill materials and the load of the overlying strata is supported by remaining coal pillar and backfill materials. Since there is little research on reasonable mining scheme for short-strip coal recovery with backfill in thick coal seam, this paper employed numerical and physical simulation to study the effect of mining sequence and the strip width on the subsidence of the overlying strata and proposed a reasonable mining scheme.

2. General situation

Sima coal mine is a typical coal mine in Luan Group, located in Changzhi, Shanxi province, China and it is chosen for the analysis. The primary mineable coal is the #3 coal seam which has a stable horizon and a simple structure. This coal seam has an average thickness of 6.4m, an average inclination of 5° and an average burial depth of 331m. The immediate roof is mudstone and the main roof is fine-grained sandstone with quartz and feldspar and a small amount of mica.

As shown in Fig.1, the mining area is located at the northeast of Sima coal mine. The mining area is about 500×500m, which is the blue region in Fig.2. The chenggong automobile factory is over the mining area and the urban expressway is near the mining area. The two structures may be affected by the mining production. The generalized stratigraphic column of Sima coal mine is shown in Fig.3.

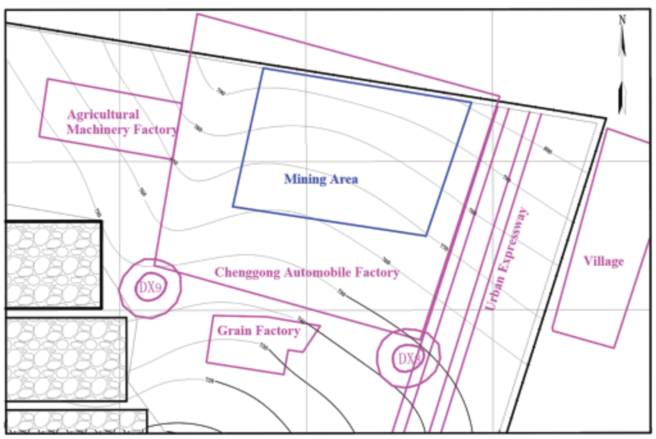

Fig.2 The mining area and surface structures of Sima coal mine

Thicknesss (m)	Lithology
76.2	Topsoil
18.2	Fine siltstone
113.3	Mudstone
19.0	Fine sandstone
30.0	Sandy mudstone
30.5	Mudstone
27.8	Sandy mudstone
6.7	Fine sandstone
4.3	Mudstone
6.4	Coal
30.0	Sandy mudstone

Fig.3. Generalized stratigraphic column

3. Numerical simulation of the reasonable mining sequence and strip width

3.1 Model in details

A comprehensive model is constructed with the metric dimension being 1500m×200m×362.15m (length×width×height) along the *x*, *y* and *z* direction in Flac3D software. The left and right sides of the model are fixed in displacement along x axial direction. The front and back sides of the model are fixed in displacement along *y* axial direction. The bottom side of the model are fixed in displacement along *z* axial direction. The model employed Mohr Coulomb criterion. Five

Table 1: Physical and mechanical parameters in numerical simulations

Lithology	Density /kg/m^3	Bulk modulus /GPa	Shear modulus /GPa	Cohesion /MPa	Tensile strength /MPa	Friction angle
Topsoil	1400	0.017	0.1	0.4	0.04	15
Fine siltstone	2500	5.0	3.75	8.7	3.21	32
Mudstone	2500	4.464	3.074	3.7	1.48	26
Fine sandstone	2500	6.0	4.32	9.5	3.59	35
Sandy mudstone	2500	4.598	3.306	3.9	2.42	30
Mudstone	2500	3.819	2.88	3.7	1.48	26
Sandy mudstone	2500	4.598	3.306	3.9	2.42	30
Fine sandstone	2500	6.0	4.32	9.5	3.59	35
Mudstone	2500	3.819	2.88	3.5	1.57	26
Coal	1300	1.94	1.46	1.8	1.0	24
Sandy mudstone	2500	4.657	4.095	3.8	2.34	28
Backfill material	1680	0.21	0.12	1.4	0.244	27

measuring lines are arranged respectively at the top of the immediate roof (4m above the coal seam), at the top of the main roof (11m above the coal seam), at the middle of the sandy mudstone (78m above the coal seam), at the top of the topsoil (289m above the coal seam) and at the surface. According to the estimation, the 19m-thickness fine sandstone is the key stratum. The final parameters of strata and backfill material are presented in Table 1.

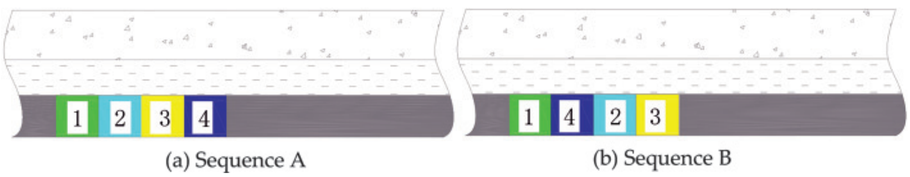

Fig.4 Mining sequence

3.2 Numerical simulation schemes

According to the constraint condition of the coal seam and the backfill material, the roof of the excavated space could be simplified as a fixed beam. By using the calculation method described by Sun [29], the strip width should be less than 8m to ensure roof stability after mining. Taking into account the equipment size and the requirement of the filling process, the minimum strip width should be no less than 4m. Therefore, the simulated strip width is selected as 4m, 5m, 6m and 7m respectively.

Two mining sequences are put forward, as shown in Fig.4: for sequence A, the next strip is adjacent to this strip; for sequence B, the next strip is spaced to the previous strip. No.1 strip is mined in the first excavation (areas filled with green). No.2, No.3 and No.4 strip are filled with light blue, yellow and blue respectively.

Table 2 Simulation schemes

No.	Strip width/m	Mining sequence
1	4	A
2	5	
3	6	
4	7	
5	4	B
6	5	
7	6	
8	7	

According to the strip width and the mining sequence, the simulation schemes are presented in Table 2.

3.3. Analysis of simulation results

3.1.1 Sequence A

The subsidence curve of overlying strata of different strip width of sequence A was shown in Fig.5. and the maximum subsidence was summarized in Table. 3.

Table 3 The maximum subsidence of overlying strata of different strip width of sequence A

Distance to the coal seam/m	Stratum	Maximum subsidence of overlying strata /mm			
		4m	5m	6m	7m
4	Immediate roof	135	156	199	228
11	Main roof	113	135	156	177
78	Sandy mudstone	48	63	79	97
289	Topsoil	27	37	47	59
326	Surface	29	39	49	63

As shown in Fig.5, with the increase of the vertical distance away from the coal seam, the maximum subsidence of overlying strata increases, the subsidence curve flattens out and the influence area gradually expands. The 19m-thickness fine sandstone is the key stratum to control the surface subsidence. The subsidence below the key stratum is relatively large and varies a lot. The subsidence above the key stratum is relatively low and tends to be synchronous.

3.1.2 Sequence B

The subsidence curve of overlying strata of different strip width of sequence B is shown in Fig.6. and the maximum subsidence is summarized in Table 4.

Fig.6 shows the subsidence of overlying strata of sequence A has a similar trend with sequence B. And it also can be seen from Table 3 and Table. 4 that:

1. The maximum subsidence of the overlying strata of sequence B is less than sequence A. The immediate roof sag of sequence B is nearly the same of sequence A under the 4m-width and 5m-width strip, but less than sequence A under the 6m-width and 7m-width strip. This indicates that the roof control of sequence B is easier than sequence A under the 6m-width and 7m-width strip. The surface subsidence of sequence B is less than sequence A. Additionally, scheme B could save construction time because there is extra waiting time for condensation of backfill material in scheme A. Therefore, sequence B is selected as the mining sequence.
2. The immediate roof sag increases by 16.4%, 14.1% and 21.9% when the strip width increases by 1m from 4m to 7m. It indicates that the roof stability of 7m-width strip is much worse than 5m-width or 6m-width strip. Therefore, the preliminary strip width is selected as 5m and 6m.

Overall, sequence B is selected as the mining sequence and the preliminary strip width is 5m and 6m.

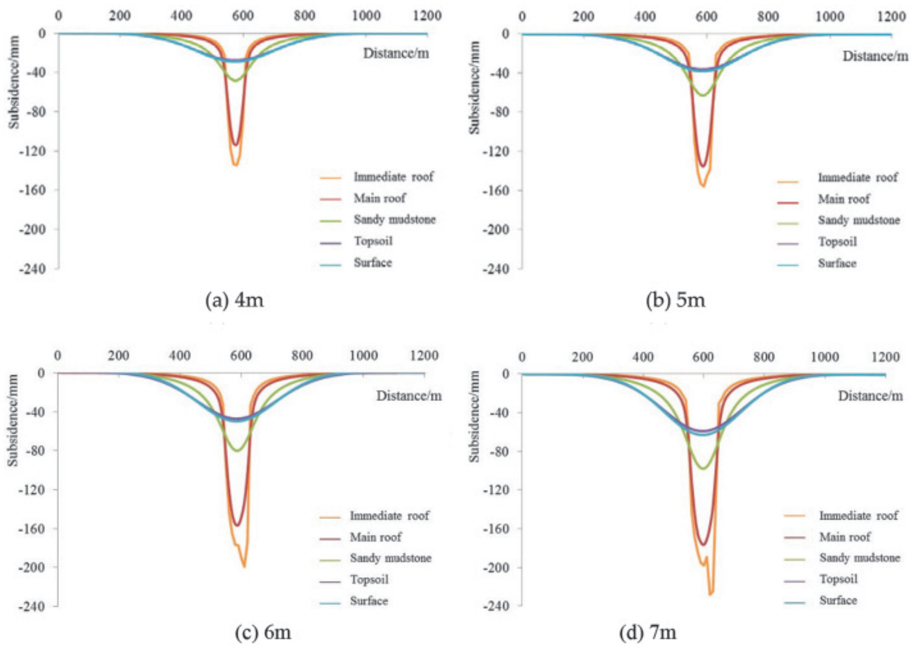

Fig.5 The subsidence curve of overlying strata of different strip width of sequence A

TABLE 4 THE MAXIMUM SUBSIDENCE OF OVERLYING STRATA OF DIFFERENT STRIP WIDTH OF SEQUENCE B

Distance to the coal seam/m	Stratum	Maximum subsidence of overlying strata /mm			
		4m	5m	6m	7m
0	Immediate roof	134	156	178	217
11	Main roof	112	135	155	173
78	Sandy mudstone	45	61	78	94
289	Topsoil	24	33	44	55
326	Surface	25	35	47	58

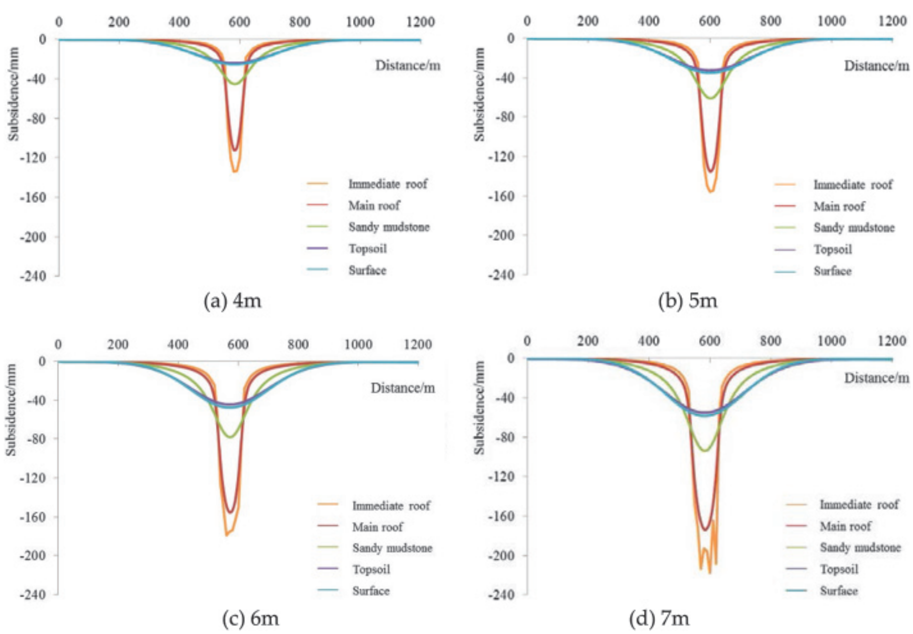

Fig.6. The subsidence curve of overlying strata of different strip width of sequence B

4. Physical simulation of the reasonable strip width

In order to determine the reasonable mining width more accurately and validate the numerical simulation results, a physical simulation is conducted to study the subsidence of overlying strata with the 5m-width and 6m-width strip respectively.

4.1 MODEL IN DETAILS

A model of 1/400linear scale is designed with a geometric dimension (length×width×height) of 2500mm×200mm×922mm. The strata distribution and mechanical parameter of prototype and model are shown in Table 5, and the ratio of similar

TABLE 5 MECHANICAL PARAMETER OF PROTOTYPE AND MODEL

Lithology	Mechanical parameter of prototype			Mechanical parameter of model		
	Thickness/m	Density /kg/m^3	Compressive strength/MPa	Thickness /mm	Density /kg/m^3	Compressive strength/MPa
Topsoil	76.2	1400	0.043	190	1500	0.00008
Fine siltstone	18.2	2500	50.2	45	1500	0.0766
Mudstone	113.3	2500	31.2	283	1500	0.0460
Fine sandstone	19.0	2500	46.3	48	1500	0.0695
Sandy mudstone	30.0	2500	55.2	75	1500	0.0828
Mudstone	30.5	2500	27.6	76	1500	0.0407
Sandy mudstone	27.8	2500	46.3	70	1500	0.0695
Fine sandstone	6.7	2500	46.3	17	1500	0.0695
Mudstone	4.23	2500	27.6	11	1500	0.0407
Coal	6.4	1300	15	16	1500	0.0401
Sandy mudstone	30	2500	36	75	1500	0.0540
Backfill material	6.35	1680	10.6	16	1500	0.0235

TABLE 6 THE RATIO OF SIMILAR MATERIALS

Lithology	Proportioning (sand: mica powder: cement)	Cement (plaster: Calcium carbonate)	Sand /kg	Mica powder /kg	Plaster /kg	Calcium carbonate/kg	Saw-dust /kg
Topsoil	86:0:4 (Sawdust 10)	2:2	131.31		3.05	3.05	15.3
Fine siltstone	80:17:3	7:3	28.93	6.15	0.76	0.32	
Mudstone	73:23:4	3:07	166.30	52.40	2.73	6.38	
Fine sandstone	80:17:3	7:03	42.62	9.06	1.12	0.48	
Sandy mudstone	73:23:4	7:03	43.97	13.85	1.68	0.72	
Mudstone	73:23:4	3:07	44.58	14.05	0.73	1.71	
Sandy mudstone	80:17:3	7:03	44.74	9.51	1.18	0.50	
Fine sandstone	80:17:3	7:03	62.36	13.25	1.64	0.70	
Mudstone	73:23:4	3:07	44.58	14.05	0.73	1.71	
Coal	90:0:6 (Sawdust 4)	3:03	11.57	0.00	0.39	0.39	0.51
Sandy mudstone	80:18:2	7:03	48.14	10.83	0.84	0.36	
Backfill material	70:23:2 (Sawdust 5)	2.54	66.61	20.99	1.09	2.55	

materials is shown in Table 6.

In this experiment, the vertical displacement of overlying strata and surface during mining is recorded by three-dimensional photogrammetric system. 539 measuring points are arranged at the front surface of the model. The measuring system is shown in Fig.7. The measuring points are reflective signs which are nailed to the model by pins and are located on the intersections of horizontal and vertical lines draw on the front surface. The horizontal lines are drawn at the height of 120mm, 220mm, 320mm, 420mm, 520mm, 620mm, 720mm, 770mm, 820mm, 870mm, 920mm and the spacing of the vertical lines are 50mm.

Two groups are arranged, group A in the left including twelve 6m-width strips and group B in the right including twelve 5m-width strips. The distance between two groups is 1100mm in order to avoid mutual influence of the two groups. After mining of each strip, it is necessary to wait for 10 minutes to provide sufficient time for the movement of the overlying strata. Afterward the excavated space is filled with backfill material and the rate of filling material of the excavated space should not be less than 90%.

4.2. ANALYSIS OF SIMULATION RESULTS

Before the analysis, the surface subsidence is selected to validate the accuracy of the numerical simulations. When the strip width is 5m, the surface subsidence is 35mm by numerical simulation and 38mm by physical simulation. While the width increases to 6m, the surface is 47mm by numerical simulation and 49mm by physical simulation. The surface subsidence shows that the physical simulation results are in good agreement with the numerical results.

The subsidence curve and the maximum subsidence of overlying strata after each strip excavation is shown in Fig.8. and Table 7 respectively.

As shown in Fig.8. and Table 7:

(1) After the first excavation, the subsidence of overlying

strata decreases gradually with the increase of the distance to the coal seam. From the completion of the first excavation to the second excavation, the subsidence of overlying strata increases rapidly; however, from the completion of the second excavation to the last excavation, the subsidence increases relatively slow.

(2) The subsidence difference between 5m-width and 6m-width strip is low after the first excavation, increases from the completion of the first excavation to the last excavation.

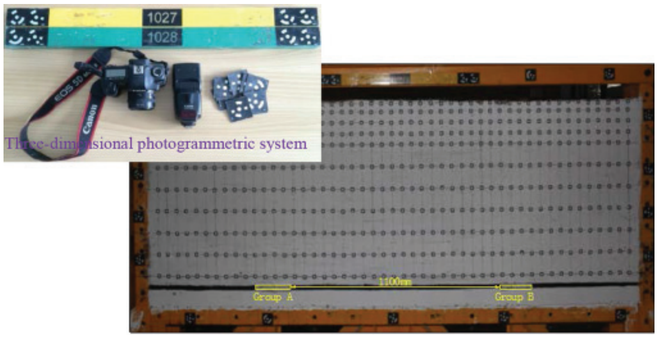

Fig.7 Measuring system

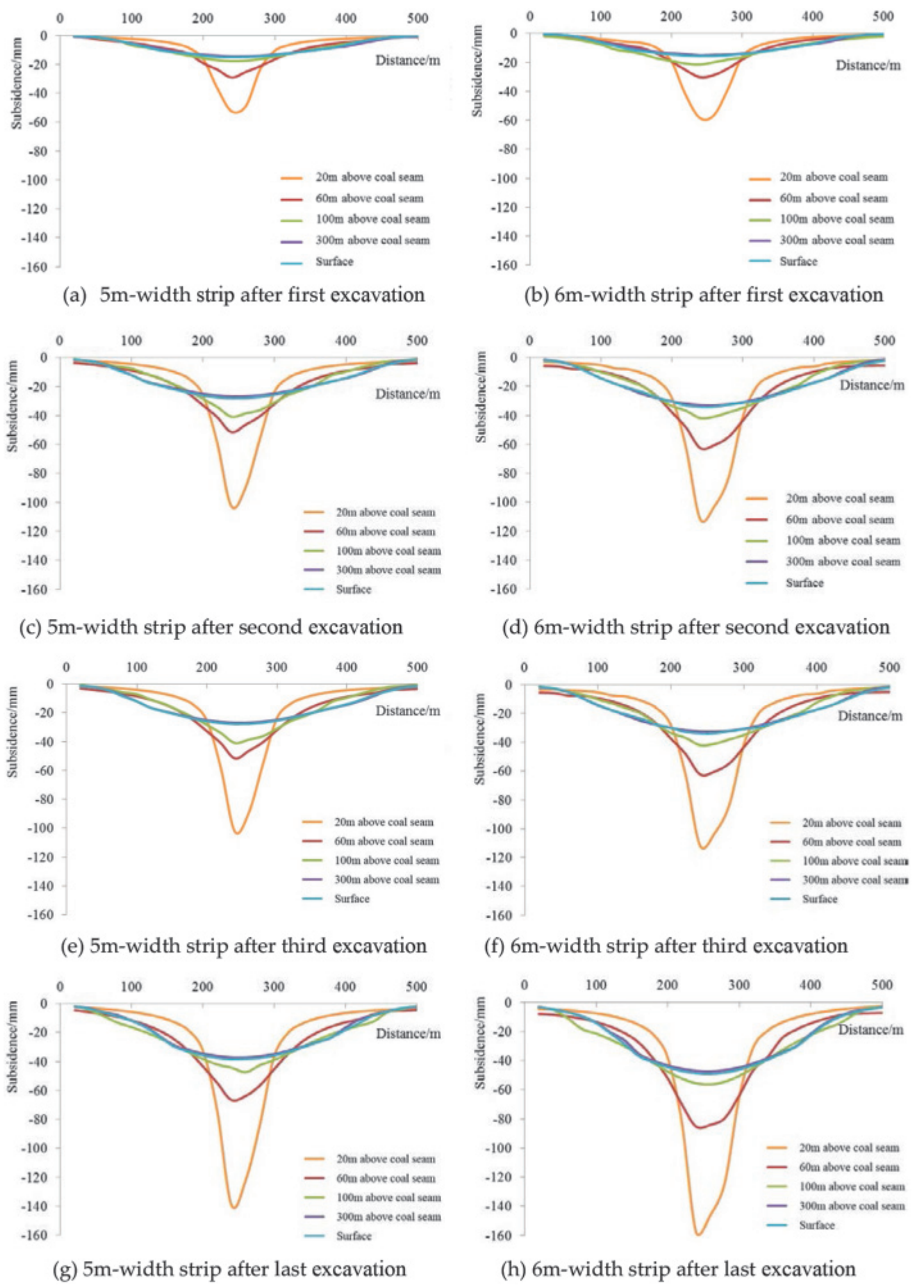

Fig.8 The subsidence curve of overlying strata after each strip excavation

(3) After the last excavation, the excavated space is filled with backfill material and both of 5m-width and 6m-width strip can ensure that the surface subsidence is controlled in an allowing range.

The difference of the final subsidence between 5m-width and 6m-width strip is relatively small. However, when taking into account the moving times of the strip face and supporting cost, the strip width is selected as 6m. For the mining area in Sima coal mine, 100 strips are needed when the strip width is 5m and 83 strips are needed when the strip width is 6m. Therefore, the strip width is finally determined as 6m.

5. Prediction of surface movement and deformation

5.1. Layout of mining area

The mining area of Sima coal mine is divided into two zones, #1 zone and #2 zone with size of 480m× 231m. A protective 20m-width coal pillar is between #1 auxiliary haulage entry and #2 auxiliary haulage entry. And there is a 3.5m-width coal pillar to protect #1 air-return entry. The layout of mining area is shown in Fig.9. There are two faces in the same time, one strip face to produce coal and one filling face to fill the excavated space.

5.2. Prediction of surface movement

According to the data obtained from Sima coal mine's surface movement observation station, its surface subsidence characteristics conform to a probability integral model. The mine's surface subsidence

TABLE 7. THE MAXIMUM SUBSIDENCE OF OVERLYING STRATA AFTER EACH STRIP EXCAVATION

Distance to the coal seam/m	Maximum subsidence/mm					
	First excavation			Second excavation		
	Strip width		Difference	Strip width		Difference
	5m	6m		5m	6m	
20	53	58	5	102	112	10
60	29	30	1	51	62	9
100	17	21	4	40	41	1
300	14	15	1	26	32	6
326	15	16	1	27	34	7
Distance to the coal seam/m	Third excavation			Last excavation		
	Strip width		Difference	Strip width		Difference
	5m	6m		5m	6m	
20	117	130	13	139	157	18
60	57	70	8	67	85	18
100	46	54	8	47	56	9
300	33	40	7	37	47	10
326	34	42	8	38	49	11

TABLE 8. THE MAXIMUM SURFACE SUBSIDENCE AND DEFORMATION

Site	Maximum surface subsidence /mm	Maximum horizontal movement /mm	Maximum Inclined deformation/ mm/m	Maximum horizontal deformation/ mm/m
Chenggong Automobile Factory	180	50	-0.6	1.3
Urban Expressway	20	26	0.3	0.4

prediction and practice over the years indicate that the calculation precision by the probability integral method can meet the precision requirements of engineering design. Probability integral method is therefore adopted to predict surface movement and deformation following exploitation in the mining area. The Mining Subsidence Prediction System, developed by the Mining Damage and Protection Research Institution of China University of Mining and Technology, is used to calculate the surface subsidence. This system is based on the probability integral method and has several engineering applications [25, 30, 31]. The surface subsidence curve in mining area is mapped as shown in Fig.10. The maximum surface subsidence and deformation of Chenggong automobile factory and urban expressway are shown in Table 8.

According to the prediction results, the maximum surface subsidence of Chenggong automobile factory is 180 mm, the maximum horizontal movement is 50 mm, the maximum inclined deformation is -0.6 mm/m, and the maximum horizontal deformation is 1.3 mm/m, the corresponding values for urban Expressway are 20mm, 26 mm, 0.3 mm/m, and 0.4 mm/m, respectively. The calculated results demonstrate that the proposed mining scheme can ensure that the damage of Chenggong automobile factory and urban expressway is less than the requirement of grade I of the rules of People's Republic of China Coal Industry Bureau.

6. Conclusions

The short-strip coal recovery with backfill method is proposed for coal recovery in thick coal seam under buildings and other structures in Sima coal mine.

Based on the numerical simulation, the effect of mining sequence and the strip width on the subsidence of the overlying strata is studied. A reasonable mining sequence and is determined and the strip width is primarily determined as

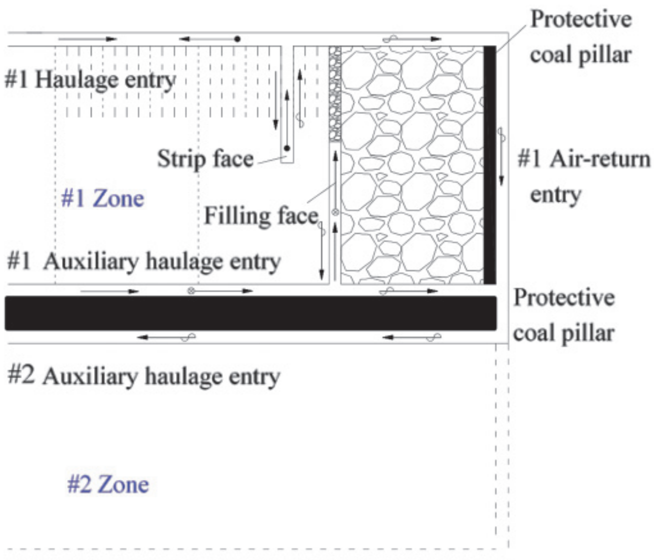

Fig.9 Layout of mining area

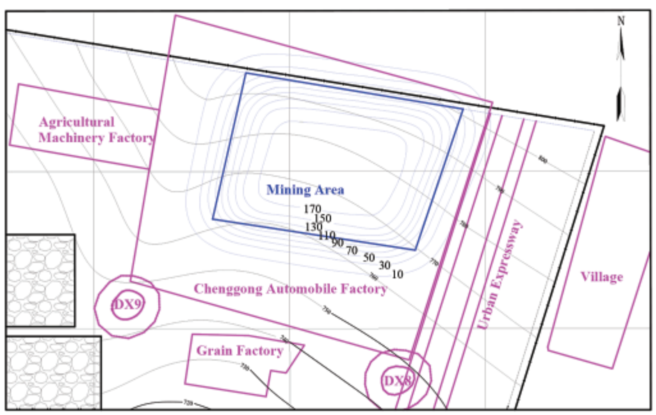

Fig.10. The surface subsidence curve

5m or 6m.According tothe physical simulation, the difference of the final subsidence of 5m-width and 6m-width strip is relatively low and both schemes could satisfy the requirement of thick coal seam recovery under buildings and other structures. When taking into account the moving times of the strip face and supporting cost, the reasonable strip width is determined as 6m.

By employing the proposed mining scheme, the surface subsidence and deformation of one building and one expressway above mining area of Sima coal mine is predicted, which shows the mining scheme can ensure the stability of the building and expressway. This paper provides a reasonable solution for coal recovery in Sima coal mine and other thick coal seams under buildings and other structures.

Acknowledgments

This paper is supported by "Priority Academic Program Development of Jiangsu Higher Education Institutions," and "the Fundamental Research Funds for the Central Universities (2017XKQY044)".

Conflicts of Interest

The authors declare no conflict of interest.

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