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ORIGINAL PAPER

Subsidence prediction method of solid backfilling mining with different filling ratios under thick unconsolidated layers

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Abstract
Solid backfill mining for coal pillar recovery in industrial squares has to ensure that the mine infrastructure, such as the shafts and substations, is not degraded or has its utility impaired by that mining. At the same time, it is important to recover as much coal as possible. As a result, it is necessary to predict mining subsidence during solid backfilling mining of coal pillars in industrial squares and to optimize the design of the working faces. At the Baishan coal mine in Anhiu province, China, there are thick layers of unconsolidated overburden above the coal seam so it is not appropriate to use the surface subsidence prediction method of equivalent mining height to predict subsidence during the mining of the coal pillars there. In order to find a reasonable coal pillar recovery scheme for the Baishan mine, a numerical simulation method is used to determine the relationships between the compression ratio of the backfilling material and the surface subsidence prediction parameters. Research was done to determine the appropriate parameters, and based on the final prediction parameters and taking the mandated protection standards for buildings and structures into account, surface subsidence is predicted and a backfill mining scheme for pillar recovery is proposed. The results show that of the six mining schemes considered, scheme 5 is the best scheme for coal pillar recovery in the industrial square at the Baishan mine. The research results are significant for similar mines with thick unconsolidated overburden anywhere in the world.

Keywords Industrial square pillar · Surface movement and deformation · Prediction parameters · Backfill mining · Thick unconsolidated layers

Introduction

Shaft sinking at the Baishan coal mine began in December, 1974, and the mine was put into operation in July 1977. After 37 years of exploitation, the designated mining area is now depleted. The next mining operation planned for the site is to recover the protective coal pillars in the industrial square. In order to ensure the safe operation of important infrastructure such as the shaft and substations, the mechanized solid backfilling mining technique is proposed for recycling the coal pillars in industrial square of Baishan mine. This technique has been used in more than 10 large mines to exploit the coal buried under buildings, water bodies, and railways. The technique has been successful. Coal mines where this method has been used include the Zhaizheng coal mine in Shandong and the Jining III of Yanzhou Coal Mine Bureau, Yangzhuang Coal Mine of Huaibei Mining Bureau, and Tangshan coal mines of Kailuan Mining Bureau and so on (Zha 2008; Guo et al. 2014; Zhang et al. 2015; Miao 2010; Miao et al., 2010; Huang et al. 2011; Li 2012).

During coal pillar recovery, important infrastructures such as the shafts and substations should not have their structural integrity compromised or their utility impaired. However, it is also necessary to maximize the amount of coal recovered and minimize the amount of backfilling materials. To attain these goals, a surface subsidence investigation needs to be carried out and working face designs need to be optimized. A number of investigators

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have conducted research on surface subsidence caused by conventional caving mining. These studies include those by Marschalko et al. (2011, 2012a, 2012b), Vakili and Hebblewhite, 2010, Aksoy et al., (2002, 2004, 2012), Singh and Yadav, 1995, Baryakh et al. 2005, Nicieza et al. 2005, Soni et al. 2007, Li et al. 2016, Guo and Xu, 2016, and Rafie and Namin, 2015. However, there are relatively few studies on surface subsidence due to backfill mining. Miao introduced the equivalent mining height theory of stratum movement for solid backfill mining and established a mechanical model for stratum movement. The mechanics of continuous media were analyzed and this allowed equations for stratum movement and surface subsidence to be derived (Miao 2012). Wang used the probability integral method to describe surface subsidence caused backfilling mining with solid compacted backfill (Wang et al. 2014). Wang also considered surface subsidence prediction based on the concept of an equivalent mining height for solid compacted backfill mining (Wang et al. 2014). Guo proposed a method for surface subsidence prediction based on stratum movement after solid backfill mining and described parameter selection for the probability integral method. This prediction method was used to estimate surface subsidence after solid backfill mining at the Huayuan mine in Shandong and the results showed that the maximum difference between actual and predicted subsidence was less than 5% (Guo et al. 2014).

As can be seen from the above summary, many current predictions about surface subsidence resulting from fully mechanized solid backfill coal mining are based on the theory of equivalent mining height. This is essentially saying that the surface subsidence caused by fully mechanized solid backfilling could be turned into caving mining of long well with equivalent height. The research cited above has demonstrated the feasibility and reliability of this prediction method by both theoretical analysis and case studies.

The Baishan mine is on the north–south axis of a small isolated coal-bearing synclinal basin. At the Baishan mine, special geological and mining conditions mean that subsidence predictions using an equivalent mining height and the related parameters directly cannot be made. Using the equivalent mining height model for coal pillar recovery and working face optimization would be unwise. The thickness of the unconsolidated Cenozoic overburden is between 114 and 176 m with an average thickness of 140 m. The mine's industrial square is located in the southwestern part of the mine and the unconsolidated layers there are 150-m thick. Obviously, this would have an effect on surface subsidence predictions. Research by Hu indicated that at some mining depths, surface subsidence and deformation were closely related to the ratio of soil and rock (the ratio of the thicknesses of the unconsolidated material to the thickness of the bedrock) (Hu 2012). Shi reported that the probability integral method could select appropriate parameters for predicting subsidence from mining under many geological and mining conditions, but for mining under thick alluvium, the thickness of the alluvium had to be taken into consideration (Shi 2016). Current engineering practice amends the probability integral method subsidence prediction parameters for layers of thick unconsolidated material.

Up to now, there has been no consensus on what prediction parameters for surface subsidence should be used when solid backfill mining is done under thick unconsolidated cover. In this paper, the finite difference software FLAC®3D (Itasca Consulting Group, Minneapolis, MN, USA) is used to establish a numerical model for solid backfill mining under thick unconsolidated overburden. The model is based on the Baishan mine's geological and mining conditions and is used to analyze the relationships between different filling ratios and surface subsidence prediction parameters. The selection of constitutive model of overlying strata in solid backfilling mining is elaborated in building the model. The predictions about surface subsidence and the optimization of the pillar recovery scheme for the Baishan mine reported in this paper are formulated according to those prediction parameters. The pillar recovery scheme also considers the government-defined protection standards for buildings and structures on the surface in the industrial square. Coal mines under thick, unconsolidated sedimentary deposits can be found all over the world. Some mines have long production histories and face mining difficulties as their reserves become depleted. Backfill mining, other filling mining methods, or sectional filling is the preferred means to exploit coal resources buried under buildings, water bodies, and railways as well as the best method to recover coal pillars under industrial squares. Therefore, the research results reported in this paper are significant for similar coal mines all over the world.

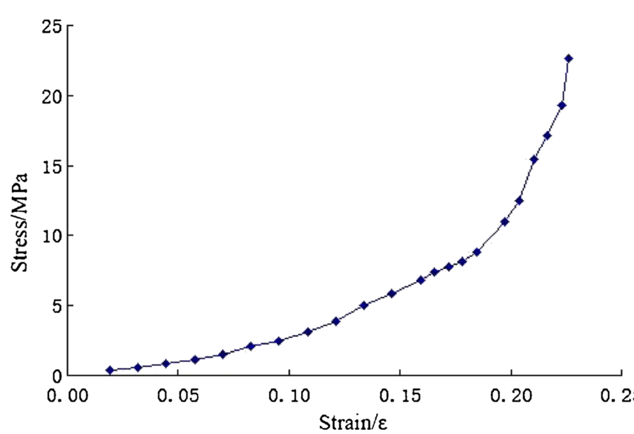

Fig. 1 Stress–strain curve for gangue from the Baishan coal mine

Table 1 Proportions of materials used to construct the similar material model of the stratigraphic section hosting the coal seam at the Baishan coal mine

Lithology	Proportion	Sand	Mica powder	Gypsum	Calcium carbonate
Floor (fine sandstone)	71:13:16 (7:3)	80.75	3.25	11.2	4.8
Coal	80:17:3 (7:3)	92.75	4.25	2.1	0.9
Sandy mudstone interbed	71:23:6 (3:7)	88.25	5.75	1.8	4.2
Siltstone	79:16:5 (5:5)	91	4	2.5	2.5
Fine sandstone	74:16:10 (5:5)	86	4	5	5
Fine siltstone interbed	74:16:10 (3:7)	86	4	3	7
Weathered mudstone	73:23:4 (5:5)	90.25	5.75	2	2
Surface soil	80:18:2 (3:7)	93.5	4.5	0.6	1.4

Relationship between subsidence prediction parameters and backfill compression ratios

There are two requirements that have to be met for pillar recovery in the Baishan mine. The first is to guarantee that any damage to the important infrastructure such as shafts and substations does not exceed the protection standards defined by the Chinese Coal Industry Bureau. The second is to maximize the tonnages of coal produced while minimizing the amount of backfilling materials used. The fill's compression ratio determines how much filling material is required. Therefore, the relationship between the backfill mining subsidence prediction parameters and how much the fill will compress under a thick layer of unconsolidated material needs to be investigated. This section uses numerical simulations to investigate the relationships between the subsidence prediction parameters and the backfilling compression ratio.

Mechanical properties and simulation method for backfill material

The material selected for backfill in the Baishan coal mine is the gangue. Gangue is the solid waste generated during mining. In the Baishan mine, the gangue has a low-carbon content and is harder than the coal; it is a dark gray sedimentary rock related to the coal seams. The way in which the gangue responds to compression and deformation has a significant influence on subsidence after backfill mining. According to an experiment run on the mechanics of Baishan mine gangue, the gangue is a bulk material and its compressive deformation can be divided into a pore collapse stage and a particle breakage stage, as shown in Fig. 1. In the first stage, the stress–strain relationship is linear. In the second stage, the stress–strain curve shows the strain hardening of the gangue on a micro level. The compression ratio η of the gangue backfill material is between 5 and 30%.

The backfill ratio of the gangue, ε, is the index for evaluating the quality of the backfilling. The equivalent mining height (Guo et al. 2014) is $m_e = m \times (1-\varepsilon)$, where m is the thickness of the coal seam. There are three main factors affecting the gangue backfill ratio. They are lacking distance of roof-contract, movement of the roof and floor before backfilling, and the compression ratio of the backfilling material. The existing fully mechanized solid backfilling equipment can ensure that the lacking distance of roof-contact and the movement of the roof and floor before backfilling are zero. Therefore, the compression ratio of the backfill becomes the main factor affecting the backfill ratio. This can be expressed as:

$$\varepsilon = 1-\eta \tag{1}$$

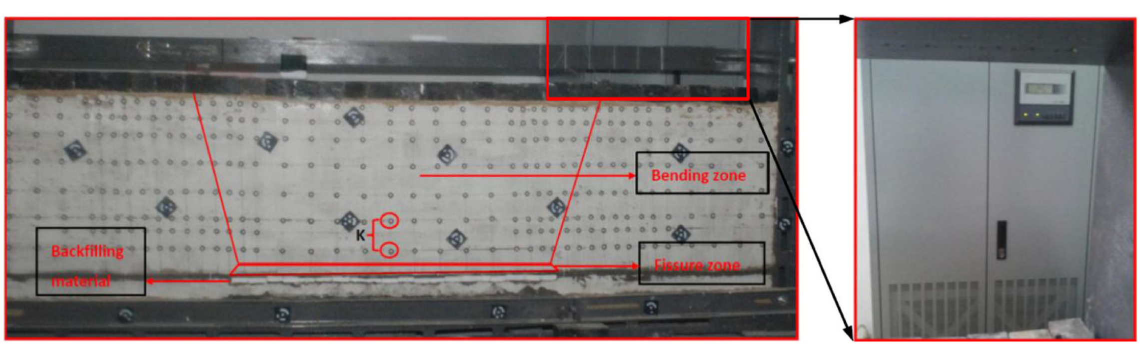

Fig. 2 Overlying stratum movement and deformation after backfilling mining

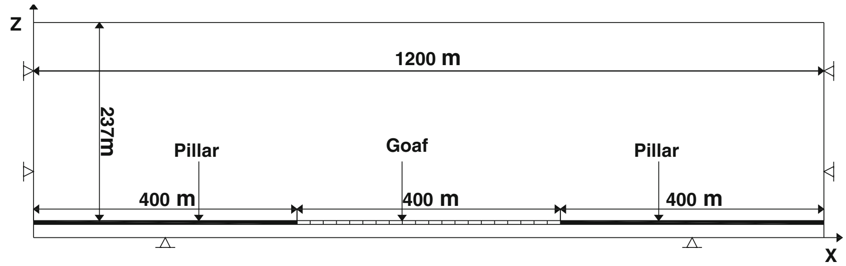

Fig. 3 Diagram showing the numerical model's geometric dimensions and boundary conditions

This paper uses numerical simulations to investigate the relationships between surface movement parameters and the backfilling ratio under thick unconsolidated deposits. Therefore, the backfilling ratio of the backfill material can be used to calculate the equivalent mining height for the numerical model. This equivalent mining height can then be used as the model's coal seam mining thicknesses with different backfilling ratios under thick unconsolidated deposits. That is, when the backfilling ratio of the backfill material changes, the thicknesses of coal seams in the numerical model also change. To make the simulations using different backfill ratios comparable, the other conditions for each model remain constant.

Constitutive model selection for overlying strata during backfilling mining

Jing proposed that the constitutive model and accurate parameter selection relate directly to the simulation results (Jing 2003). Therefore, it is necessary to use an appropriate constitutive model of the overlying strata to obtain accurate simulation results. The constitutive model used for a rock mass being mined is commonly the Mohr–Coulomb model. Mahdi pointed out that during long-wall caving mining, more reasonable and reliable simulation results can be obtained by using a strain-softening model to study the rock in fractured zones (Mahdi and Li, 2012). To study the overlying strata's settling behavior after backfill mining and to determine the appropriate constitutive model, a similar material simulation is adopted. The essence of a similar material model is to reduce the size of the strata by a certain proportion and make a physical model with similar materials according to similar principles. Then, the model can be used to simulate the mining, and the overlying stratum movement and destruction conditions can be observed. Finally, the real rock stratum conditions can be analyzed and predicted by combining the model results and the similar principles (He et al.1991). Zhu analyzed sources of error in similar material models and showed that temperature and humidity changes can cause errors (Zhu et al. 1984). To eliminate the influence of temperature and humidity errors, the similar material model was built under constant temperature and humidity conditions. In the mining field, river sand and mica powder are often used as base materials, and gypsum and calcium carbonate are used as the cemented materials. In this experiment, river sand, mica powder, gypsum, and calcium carbonate were used to construct the physical model of the unconsolidated layers, coal, and rock at the Baishan mine. Meanwhile, sheet mica is put between layers to show the effect of rock mass joint. The proportions of sand, mica, gypsum, and calcite used to simulate geologic formations in the physical model are listed in Table 1.

The dimensions of the physical model are 3 m × 0.3 m × 1.1 m. The mining area, 1 m in length, is located in the middle of the model with a non-mined boundary layer 1 m in length on each side. The coal layer needs to be excavated for 20 times. Figure 2 shows the deformation (subsidence) in the

Table 2 Mechanical properties and thicknesses of the six lithologic units represented in the FLAC3D numerical model

Rock type	Bulk modulus (GPa)	Shear modulus	Tensile strength (MPa)	Cohesion (MPa)	Internal friction angle (°)	Thickness (m)	Height (m)
Siltstone 1	3.24	2.84	2.48	2.48	33.11	30	30
Coal seam	1.07	0.70	1.4	2.29	31.51	3	33
Fine sandstone	1.49	1.52	1.8	4.79	35.19	5	38
Siltstone 2	1.88	1.07	1.7	2.48	33.11	52	90
Mudstone	1	0.57	1.6	2.03	29.14	30	120
Unconsolidated layers	0.41	0.19	0.01	0.01	15.0	150	270

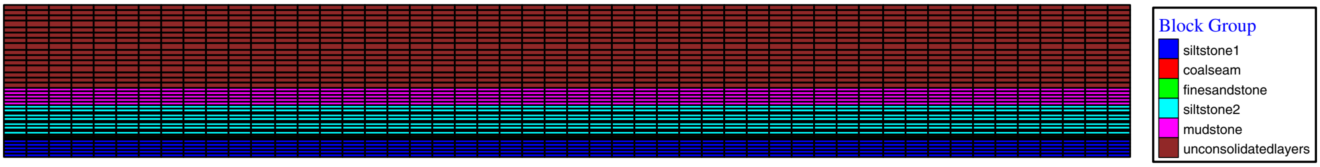

Fig. 4 Diagram showing the lithologic layering in the numerical model

overlying strata after mining in the model. As can be seen in the figure, the caving zone is not generated in the overlying strata and the cracks are small. The somewhat subtle bending zone has been generated in the center of the model but the strata are continuous across the zone. For the continuous strata, the Mohr–Coulomb constitutive model is commonly used for geotechnical engineering. Thus, a Mohr–Coulomb model can be adopted as the constitutive model for the overlying strata in the gangue backfill mining.

Numerical modeling

The mining depth in the industrial square at the Baishan coal mine is 237 m; the mining thickness is 3 m. The aggregate thickness of the unconsolidated layer is 150 m and the coal seams are nearly horizontal. The FLAC®3D software is used to establish the numerical model. The rock strata used in the model have been simplified and the simplified lithologies are, from bottom to top, siltstone, coal seam, fine sandstone, siltstone, mudstone, and the unconsolidated layer. The mechanical properties of these lithologies are listed in Table 1. The constitutive model used is the Mohr–Coulomb model.

The model uses a rectangular coordinate system with the *x*–*y* directions in the horizontal plane and the *z*-axis vertical. The strike of the coal seam is parallel to the *x*-axis. The model's design simulates a mining panel measuring 400 m along the strike and 400 m along the dip of the coal seam. A step-by-step method is used for the simulated excavation. There are 20 excavation steps with each step excavating 20 m of simulated coal seam. To eliminate boundary effects and replicate actual surface subsidence, 400-m coal pillars are left on all four sides of the excavated portion of the coal seam. The model size is 1200 × 1200 × 270 m with 21,600 units and 28,830 nodes. Boundary conditions of the model are lateral horizontal displacement constraints, a vertical displacement constraint on the bottom, and free boundary on the top, as shown in Fig. 3. Table 2 lists the mechanical properties and thicknesses of the lithologic layers represented in the model. Figure 4 shows the numerical model.

Surface movement simulation schemes and results

Nine models have been created to investigate the relationships between the Baishan coal mine surface movement prediction parameters and the compression ratio quantitatively. The models' backfilling ratios are 0, 60, 65, 70, 75, 80, 85, 90, and 95% and the corresponding mining heights are 3000, 1200, 1050, 900, 750, 600, 450, 300, and 150 mm, respectively. Table 3 shows the individual schemes and the results. To make the simulation results more comparable, the models' boundary conditions and rock strata are the same. Analysis of the results indicates that the main influence propagation angles during full caving mining and the fully mechanized backfill mining are approximately the same and the displacement distance of the inflection point can be set to zero (Guo et al. 2014).

Therefore, the following sections mainly discuss the relationships between the subsidence coefficient, the horizontal movement coefficient, and the tangent to the major influence angle to the backfilling ratio during backfill mining.

Table 3 Subsidence and surface movement results from simulation schemes testing different backfill compression ratios

Scheme	Compression ratio	Max. subsidence/m	Max. horizontal movement value/m	Subsidence coefficient	Horizontal movement coefficient	Tangent of major influence angle	Remarks
1	95%	107.0	39	0.71	0.36	0.73	Same rock stratum parameters
2	90%	214.8	78	0.72	0.36	0.76	
3	85%	322.5	115	0.72	0.36	0.78	
4	80%	430.0	154.7	0.72	0.36	0.8	
5	75%	540.0	197	0.72	0.36	0.81	
2'	70%	651.2	234.8	0.72	0.36	0.82	
3'	65%	758.5	280	0.72	0.37	0.83	
4'	60%	865.5	318	0.72	0.37	0.84	
5'	0	2260.0	871.9	0.75	0.39	0.91	

Backfill mining simulation results

To illustrate the relationships between the backfilling ratios and surface movement prediction parameters during backfill mining, Fig. 5 was constructed from the data in Table 3.

As shown in Fig. 5, during backfill mining under a thick unconsolidated layer, the backfilling ratio has an inverse relationship with the subsidence coefficient, the horizontal movement coefficient, and the tangent of major influence angle. That is, as the compression ratio increases, the subsidence coefficient, horizontal movement coefficient, and the tangent of major influence angle decrease. However, how much each coefficient or the angle changes as the backfilling ratio increases is different. When the backfilling ratio increases from 0 to 60%, the subsidence coefficient is reduced to 4%; when the backfilling ratio increases from 60 to 90%, the subsidence coefficient remains unchanged; when the backfilling ratio increases from 90 to 95%, the subsidence coefficient decreases by 1%. For the entire range of backfilling ratio change, 0–95%, the subsidence coefficient decreases a total of 5%. When the backfilling ratio increases from 0 to 60%, the horizontal movement coefficient decreases 5%; when the backfilling ratio increases from 65 to 70%, the horizontal movement coefficient decreases 3%; when the backfilling ratio increases from 70 to 95%, the horizontal movement coefficient remains unchanged. For the entire range of backfilling ratio change, 0–95%, the horizontal movement coefficient decreases by a total of 8%. When the backfilling ratio increases from 0 to 95%, the tangent of major influence angle becomes smaller with each increase in backfilling ratio, and in total, it is reduced by 20%. Therefore, for surface subsidence predictions at the Baishan coal mine, the surface movement and deformation prediction parameters should be adjusted based on the backfilling ratios if one is to arrive at the best pillar recovery scheme possible.

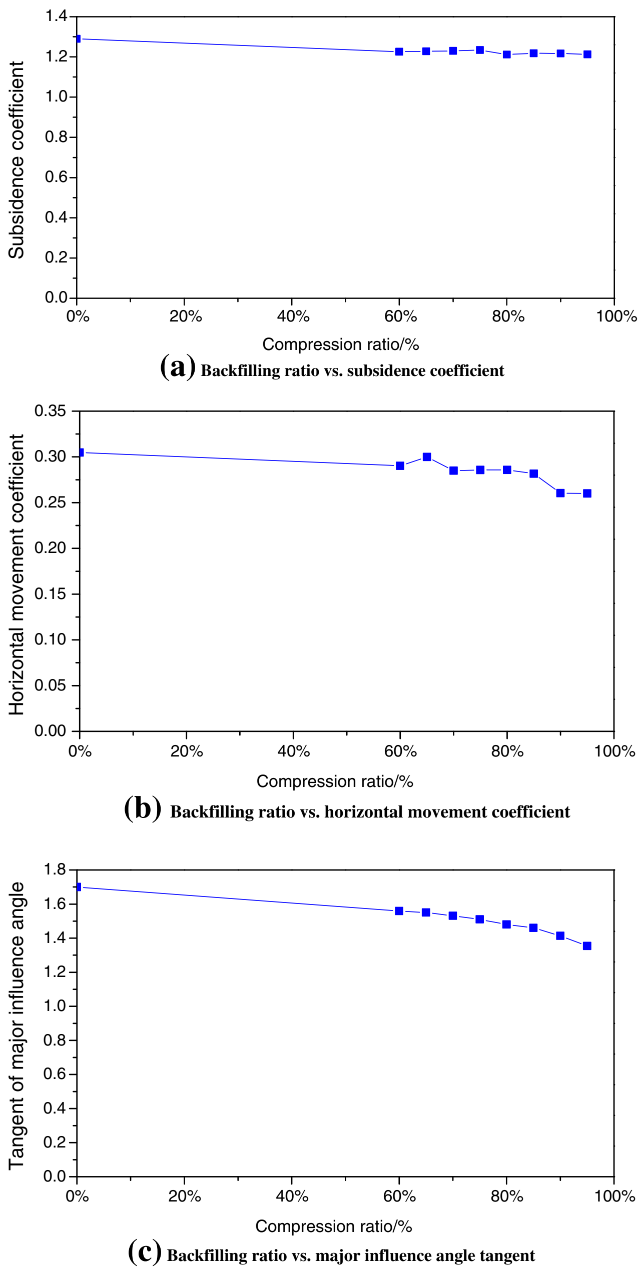

Fig. 5 Graphs showing the relationships between the backfilling ratios and the surface movement prediction parameters. **a** Backfilling ratio vs. subsidence coefficient. **b** Backfilling ratio vs. horizontal movement coefficient. **c** Backfilling ratio vs. major influence angle tangent

Buildings and structures in the industrial square and the subsidence damage protection standards

The condition of buildings and structures in the Baishan mine's industrial square and the building protection standards are the basis for the mine's coal pillar recovery design scheme. This section introduces the structures in the industrial square and defines the protection standards.

Types of buildings and structures in the industrial square

The protective coal pillars in the Baishan mine industrial square support an area totaling 0.578 km^2 and mining influences an area of approximately 1.508 km^2. The areas in the industrial square with many buildings are outlined in Fig. 6. The buildings in the industrial square include the main and auxiliary shafts, substations, plants, oil depots, lamp stations, bathrooms, canteens, water towers, office buildings, hotels, apartment buildings, and worker's houses.

The structures in the area are built with several kinds of materials. They are mainly brick-concrete, concrete, and masonry structures. The sizes of the buildings and structures are quite varied. There are one-story houses, two- and multi-story buildings, and water towers and transmission towers of different heights. There are also great differences in the length of worker's houses, shops, office buildings, and plants. Built in the 1980s, most buildings are old and some houses have cracks. Photographs of some of the buildings in the area are shown in Fig. 7.

Mining-induced damage protection standards

According to Article 27 of Document No. 81 in "Regulations on Mining and Coal Pillar Design under Building, Water body, Railway and Main Shaft" (hereinafter referred to as the Regulation) issued by the Chinese Coal Industry Bureau in 2000, damage to brick-concrete buildings less than 20 m in length or buildings with deformation joints can be divided into four levels based on the degree of damage and the surface deformation (Jin and Mou, 2000). Comparatively speaking, the infrastructure around the shafts such as the substations and office buildings and the workers' houses are more sensitive to mining-induced deformation. This deformation may impair the safe operation of production systems or cause serious social problems. Therefore, the protection standard for these areas should be set to level I and the surface movement and deformation shall not exceed the following specifications:

> Subsidence 300 mm; horizontal deformation 2.0 mm/m; inclined deformation 3.0 mm/m.

The protection standard for other areas in the industrial square is set to level II. The specifications for level II protection are:

> Subsidence 600 mm; horizontal deformation 4.0 mm/m; inclined deformation 6.0 mm/m.

Mining scheme comparisons

Mining schemes

The fully mechanized solid backfill mining method is used for coal pillar recovery in the Baishan mine industrial square. The backfilling materials are surface and underground gangues. Firstly, the professional feeding well is used to transport the surface gangues into the well which will be sent to the tail of the working face. Then, the action of filling behind supports can be realized by using the tail beam of supports to suspend the scraper conveyor. At the same time, the filled solid materials are pressed by the pushing devices of the supports, thus improving the compaction degree and obtaining the optimal solid backfilling effect.

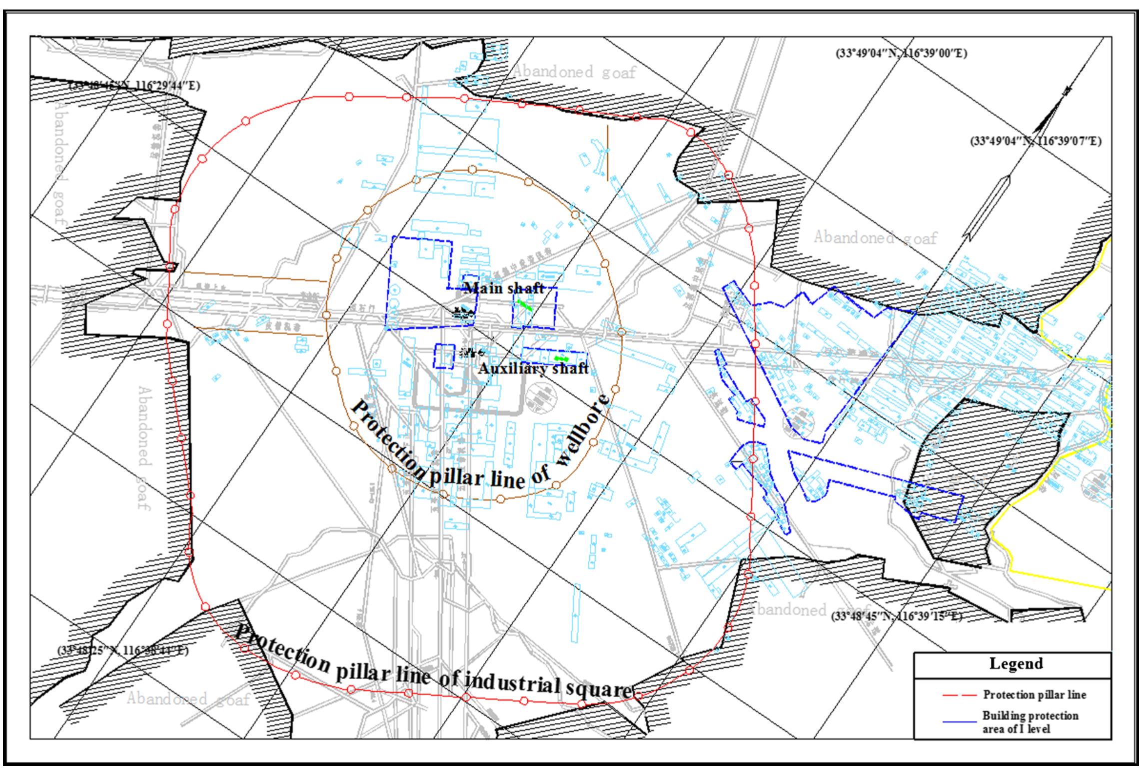

Fig. 6 Map of the industrial square and surrounding area at the Baishan mine with the built-up areas outlined

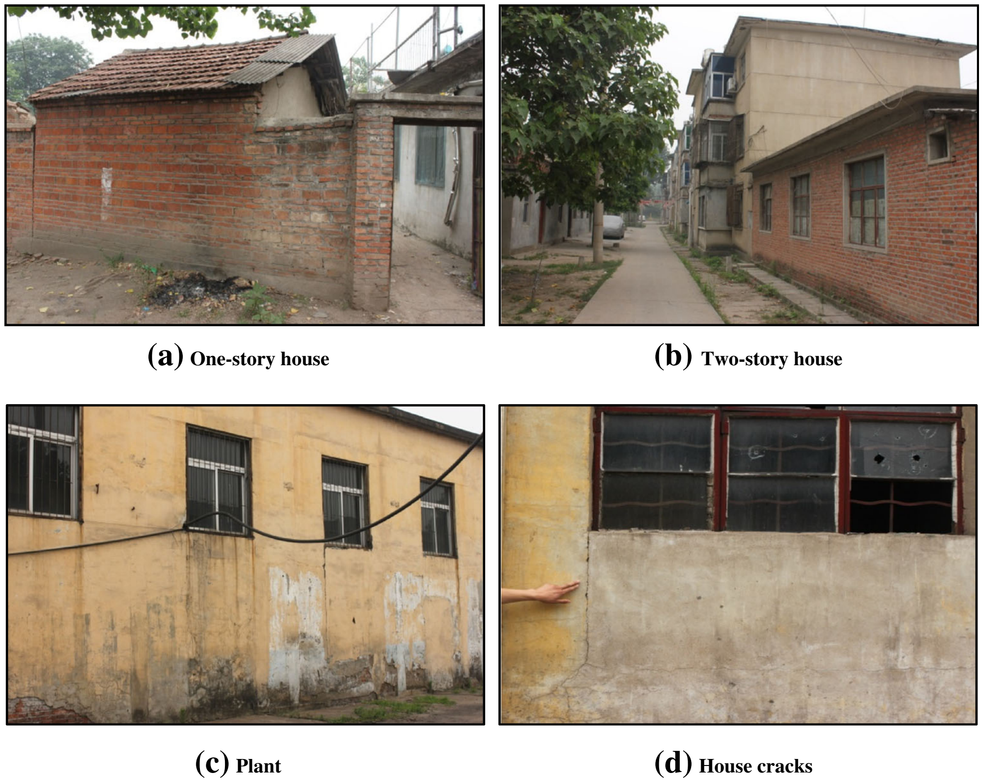

Fig. 7 Buildings in the Baishan mine industrial square. **a** One-story house. **b** Two-story house. **c** Plant. **d** House cracks

Given that the safety operation of the shafts is the basis for the coal pillar recovery, so, the protective coal pillars of shafts are remained based on surface movement angle parameters of Baishan coal mine and the Regulation. Coal pillar recovery is divided into two stages. The first stage is to recover the non-protective wellbore pillars; the

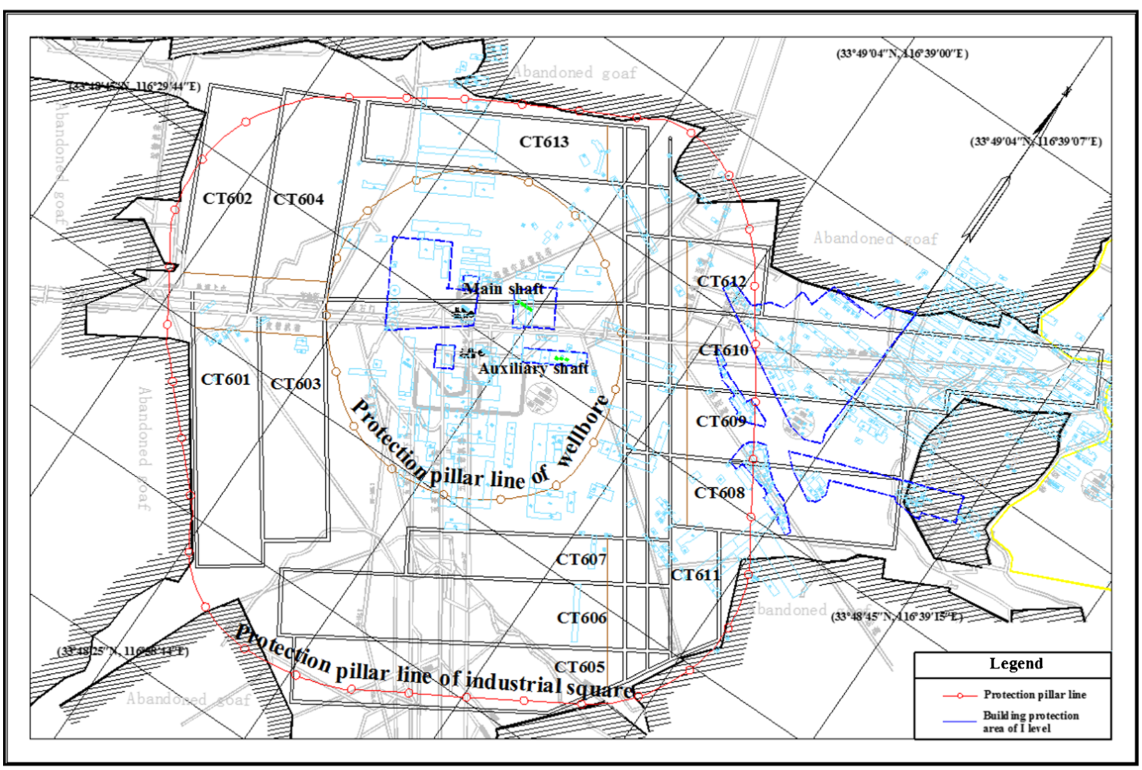

Fig. 8 Working faces (numbered CT601 through CT613) of the coal pillars to be recovered in the Baishan coal mine

second stage is to recover the protective wellbore pillars. There are 13 working faces in the coal pillar recovery operation. These faces are numbered sequentially as faces CT601 through CT6013 and are shown in Fig. 8. CT601 is the first mining face.

Based on the recoverable pillars' positions and the locations and the surface buildings' construction, six mining schemes have been designed to recover the industrial square's pillars. The schemes are:

Scheme 1: Backfill mine working faces CT601 through CT6013 with the backfilling ratio of 75%.
Scheme 2: Backfill mine working faces CT601 through CT6013 with the backfilling ratio of 80%.
Scheme 3: Backfill mine working faces CT601 through CT6013 with the backfilling ratio of 85%.
Scheme 4: Backfill mine working faces CT601 through CT6013 with the backfilling ratio of 90%.
Scheme 5: Backfill mine all the working faces except for the faces CT609, 611, and 612 with the backfilling ratio of 80%. The original working faces, faces CT609, CT6011, and CT6012, are not mined.
Scheme 6: Backfill mine working faces CT6010 and CT608 with the backfilling ratio of 85%. The other working faces, except for faces CT609, 6011, and 6012, that are backfill mined with the backfilling ratio of 80%. The original working faces, faces CT609, CT6011, and CT6012, are not mined.

Surface movement prediction parameters

The prediction parameters for surface movement and deformation are the primary data for the coal pillar recovery schemes. During backfill mining under the thick unconsolidated layer, these prediction parameters are closely related to the backfilling ratio, so the prediction parameters need to be adjusted according to the backfilling ratio. The Baishan mine's parameters of the probability integral method for surface subsidence are obtained from inversion of measured data from 675 mining face blasts. These parameters are listed in Table 4.

Table 4 Parameters of the probability integral method for surface subsidence at the Baishan mine

Subsidence coefficient	Horizontal movement coefficient	Tangent of major influence angle	Mining influence propagation angle	Displacement of inflection point
$q = 1.29$	$b = 0.2$	1.7	89°	0.07 H

Table 5 Parameters of the probability integral method for surface subsidence after caving mining calculated from the empirical formula provided by the Chinese Coal Industry Bureau

Subsidence coefficient	Horizontal movement coefficient	Tangent of major influence angle	Mining influence propagation angle	Displacement of inflection point
$q = 0.95$	$b = 0.30$	2.01	87.9°	0

The empirical formula for surface subsidence prediction parameters for the Huaibei coal mine is listed in the Regulations. Based on the Baishan mine's geological and mining conditions, the related surface subsidence prediction parameters can be calculated from this formula; they are listed in Table 5.

In light of the basic laws of surface movement and deformation under thick unconsolidated layers and the protection of buildings, the prediction parameters of the probability integral method after caving mining, listed in Table 6, are selected to further refine the Baishan subsidence prediction parameters (see below).

The prediction parameters of surface movement and deformation during backfill mining are closely related to the backfilling ratio. For this reason, the relationship between the prediction parameters and the backfilling ratio was analyzed in Section 2 of this paper. According to the results in that section and the surface subsidence prediction parameters listed in Table 6, the final prediction parameters (Table 7) for the Baishan mine are obtained. During subsidence prediction, the prediction parameters of surface movement and deformation should be adjusted according to the backfilling ratio.

Mining scheme comparisons

The probability integral method is widely used for surface subsidence prediction models in the mining industry. Many years of practice show that the method's precise predictions of surface subsidence can fully meet engineering requirements (He et al. 1991). In addition, the

Table 6 Parameters of probability integral method for surface subsidence in the Baishan coal mine

Subsidence coefficient	Horizontal movement coefficient	Tangent of major influence angle	Mining influence propagation angle	Displacement of inflection point
$q = 1.29$	$b = 0.30$	1.7	87.9°	0

Table 7 Subsidence prediction parameters for backfill mining in the Baishan mine

Compression ratio	Subsidence coefficient	Horizontal movement coefficient	Tangent of major influence angle	Propagation angle of mining	Displacement of inflection point
0	1.29	0.30	1.7	87.9°	0
60%	1.24	0.28	1.57	87.9°	0
65%	1.24	0.28	1.55	87.9°	0
70%	1.24	0.28	1.53	87.9°	0
75%	1.24	0.28	1.51	87.9°	0
80%	1.24	0.28	1.49	87.9°	0
85%	1.24	0.28	1.46	87.9°	0
90%	1.24	0.28	1.42	87.9°	0
95%	1.22	0.28	1.36	87.9°	0

probability integral method of equivalent mining height can be used to predict surface subsidence after solid backfilling mining (Guo et al. 2014). In this paper, the probability integral method is also used to calculate the surface movement and deformation for the six mining schemes described at the end of Section 4.1. Because of space limitations, this paper only provides one surface subsidence contour map, namely Fig. 9, a contour map of surface subsidence after backfilling mining using scheme 6. Table 8 lists each scheme's surface movement and deformation as well as the damage to the surface buildings and structures.

As is shown by the figures in Table 8, the mining-induced damage to the buildings near the shafts is more than level II for schemes 1 and 2, and the damage to other buildings in the industrial square is also more than level II. For schemes 3 and 4, the damage to buildings around the shafts is more than level I and the damage to other buildings in the industrial square is no more than level II. For schemes 5 and 6, the damage to buildings near the shafts is no more than level I and the

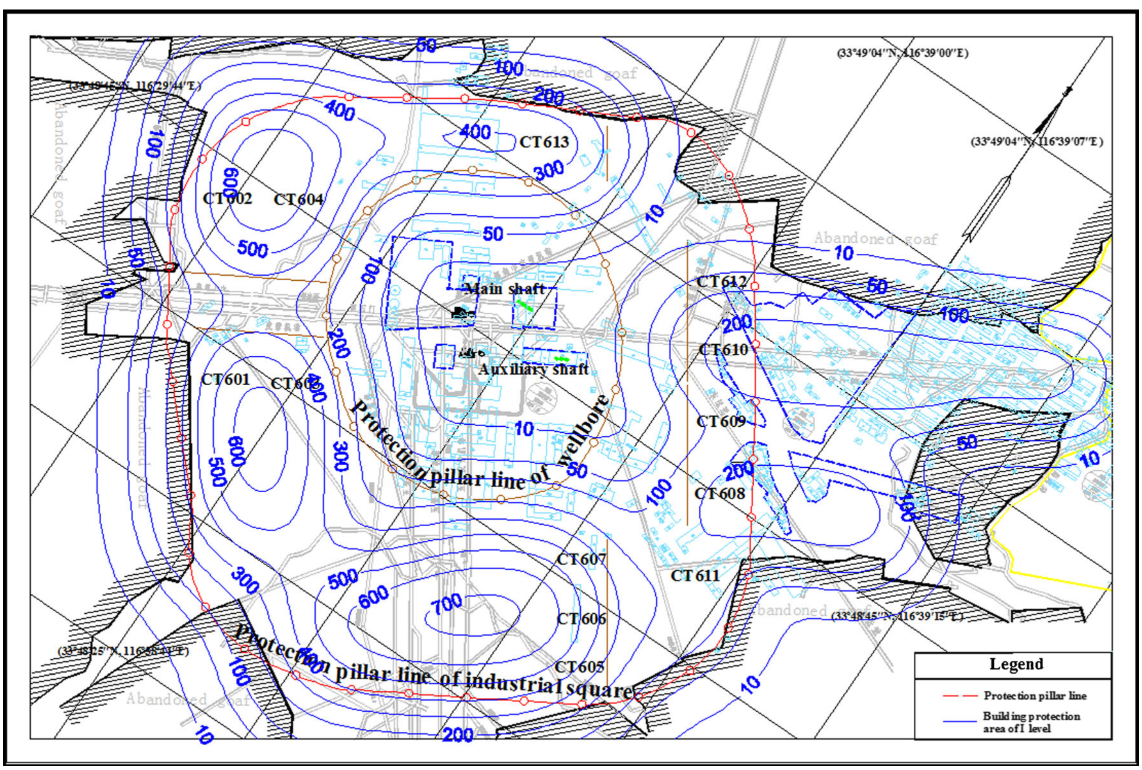

Fig. 9 Map showing contours (in mm) of predicted surface subsidence after scheme 6 backfill mining for pillar recovery in the industrial square at the Baishan mine

Table 8 Surface movements and resultant damage level to buildings and structures for each backfill mining scheme

Scheme	Fortification level	Direction	Subsidence/ mm	Horizontal movement/ mm	Inclination mm/m	Horizontal deformation mm/m	Curvature mm/m^2	Damages
Scheme 1	Level I	S-N	875.2	225.7	6.23	3.09	0.08	III
		E-W		225.7	6.23	3.09	0.10	
	Level II	S-N	875.2	225.7	6.23	3.09	0.08	III
		E-W		225.7	6.23	4.35	0.16	
Scheme 2	Level I	S-N	700.0	180.0	5.00	2.50	0.06	III
		E-W		180.0	5.00	2.50	0.08	
	Level II	S-N	700.0	180.0	5.00	2.50	0.06	III
		E-W		180.0	5.00	3.50	0.12	
Scheme 3	Level I	S-N	525.7	135.2	3.76	1.87	0.05	II
		E-W		135.2	3.76	1.87	0.06	
	Level II	S-N	525.7	135.2	3.76	1.87	0.05	II
		E-W		135.2	3.76	2.62	0.09	
Scheme 4	Level I	S-N	350.4	90.1	2.53	1.25	0.03	II
		E-W		90.1	2.53	1.25	0.04	
	Level II	S-N	350.4	90.1	2.53	1.25	0.03	II
		E-W		90.1	2.53	1.75	0.06	
Scheme 5	Level I	S-N	265.9	128.0	2.63	2.10	0.04	I
		E-W		80.0	3.24	2.62	0.05	
	Level II	S-N	506	162.0	4.10	2.70	0.05	II
		E-W		181.0	3.70	3.10	0.06	
Scheme 6	Level I	S-N	200	96.0	2.00	1.50	0.03	I
		E-W		60.0	2.50	2.00	0.04	
	Level II	S-N	500	160.0	4.00	2.50	0.05	II
		E-W		180.0	3.50	3.00	0.06	

damage to buildings in the industrial square is no more than level II. It is clear that schemes 5 and 6 can meet the protection requirements for the buildings and structures after coal pillar recovery. The other schemes cannot. Scheme 5 uses less backfilling materials than scheme 6, so the Baishan coal mine should adopt scheme 5 for the recovery of coal pillars in the industrial square.

Conclusions

To solve the Baishan coal mine's technical problem with coal pillar recovery in the industrial square, the numerical simulation method is used to determine the relationships between the prediction parameters for surface subsidence and the backfilling ratio during the backfill mining under the thick unconsolidated layers. Based on the final prediction parameters and the results of six scenarios using different backfill mining schemes, the surface subsidence during coal pillar recovery is predicted. Based on those subsidence predictions and the protection standards for buildings and structures in the area, the most reasonable pillar recovery scheme is found. The main conclusions of this study are:

1. The caving zone is not generated in the overlying strata after solid backfill mining and only tiny fractures can be found. Most areas are in the bending zones. The rock stratum structures are continuous. The Mohr–Coulomb model could be selected as the constitutive model during the numerical simulation of backfilling mining.
2. The prediction parameters for surface movement and deformation are closely related to the backfilling ratio during backfilling mining. The subsidence coefficient, the horizontal movement coefficient, and the tangent of major influence angle have an inverse relationship with the backfilling ratio. When the backfilling ratio increases from 0 to 95%, those three factors will decrease by 5, 8, and 20%, respectively. Therefore, the prediction parameters for surface movement and deformation should be adjusted according to different backfilling ratios to better predict the surface subsidence during backfill mining.
3. Based on the final prediction parameters and the protection standards for buildings and structures in the industrial square, the probability integral method is used to calculate the surface movement and deformation after backfill mining. The results indicate that scheme 5 is the optimal scheme for the coal pillar recovery in the industrial square of the Baishan coal mine.

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