Bulletin of Engineering Geology and the Environment (2019) 78:6235–6248
https://doi.org/10.1007/s10064-019-01485-3

ORIGINAL PAPER

Surface subsidence prediction method of backfill-strip mining in coal mining

Xiaojun Zhu[1,2,3] · Guangli Guo[3] · Hui Liu[1,2] · Xiaoyu Yang[4]

Received: 11 July 2018 / Accepted: 15 February 2019 / Published online: 15 March 2019

Abstract
Intensive and massive coal mining causes a series of geological hazards and environmental problems, especially surface subsidence. In recent years, backfill-strip mining has been applied to control mining subsidence in order to realize sustainable development of the mining environment. To accurately predict the surface subsidence of backfill-strip mining, a prediction method of subsidence superposition of backfill-strip mining is proposed on the basis of the traditional probability integral method prediction model. In analyzing the distribution of the actual subsidence space, the surface subsidence problem of backfill-strip mining can be regarded as the superposition of surface subsidence caused by backfill mining and strip mining. Then, the appropriate prediction parameters will be chosen, and the surface subsidence caused by the backfill mining and strip mining will be predicted separately. The surface subsidence values of the backfill-strip mining are equal to the superposition subsidence values predicted by the backfill mining and strip mining prediction method at the same surface location. A similar material model and a numerical simulation model have been built to verify the feasibility and accuracy of the superposition prediction method. The comparison results of the surface subsidence values show that the superposition surface subsidence prediction method is reasonable. The average relative error of this superposition prediction method is less than 6.7%, and its accuracy is 3.9%~11.4% higher than that of the conventional prediction method. The superposition prediction method can satisfy the precision requirement of engineering applications. This study provides a scientific technical reference for safe mining engineering design and surface disaster protection for backfill-strip mining.

Keywords Backfill-strip mining · Coal underground mining · Surface subsidence · Prediction method · Probability integral method

Introduction

China is a major coal mining country, and its coal production reached 3.41 billion tons in 2016. However, intensive and massive coal mining causes a series of geological hazards and environmental problems (Bian et al. 2012; Chen et al. 2018; Salmia et al. 2017), such as surface subsidence, ground fissures, landslides, land occupation, and groundwater pollution. Among these, coal mining subsidence considerably impacts on the environment and societies, and can lead to damage of infrastructures, buildings, roads, and drainage systems (Lamich et al. 2016; Rošer et al. 2018). In recent decades, associated surface subsidence problems have become progressively serious with increased mining activities. Statistical data show that the total mining subsidence area in China is around 6×10^3 km^2, and that it increases annually by approximately 240 km^2 (Guo et al. 2011). Therefore, mining subsidence has become a severe social and environmental problem.

Many technologies can be applied to control mining subsidence to ensure mining safety and achieve environmental protection goals. Subsidence control technologies can be divided into two classes, namely, partial mining (Ghasemi et al.

✉ Xiaojun Zhu
zhuxiaojnuahu@126.com

[1] Collaborative Innovation Center for Mines Environmental Remediation and Wetland Ecological Security, Anhui University, Hefei 230601, People's Republic of China

[2] School of Resources and Environmental Engineering, Anhui University, Hefei 230601, People's Republic of China

[3] School of Environment Science and Spatial Information, China University of Mining and Technology, Xuzhou 221008, People's Republic of China

[4] Department of Engineering Management, Hefei College of Finance and Economics, Hefei 230601, People's Republic of China

2014) and backfill mining (Abdelhadi et al. 2016; Huang et al. 2017). However, the cost of backfill mining is high (Zhu et al. 2016) and strip mining has a low recovery ratio. Given the high cost of backfill mining and the shortage of backfill material, the concept of backfill-strip mining (Xie et al. 2004; Chen et al. 2011; Xu et al. 2007; Chen et al. 2016; Huang and Lai 2016) was proposed to solve problems such as expensive filling costs, low recovery rates and surface subsidence.

Backfill-strip mining is a partial backfilling technology that combines the advantages of backfill mining and strip mining. In this technology, longwall partial backfill mining is conducted first. After the backfill materials achieve a certain bearing capacity, the residual coal pillar is recycled. A schematic of the backfill-strip mining process is shown in Fig. 1. This mining process eventually forms a combined support structure of the filling body and the coal pillar to support the overlying strata and achieve the goal of subsidence control. Since the coal seams are shallow and the surface is covered with thick sandy soils, shallow coal seam mining usually causes more severe surface subsidence compared to deep coal seam mining (Huang 2002), and buildings are more vulnerable to damage. So, backfill-strip mining can be applied in shallow coal seam extraction under buildings due to the subsidence control effect.

In underground mining, surface subsidence prediction is an integral part of mine design. It can be used to assess possible influences of subsidence on the surface structures and the surrounding environment, and to improve mine design and thus reduce the severity of the subsidence effects. Meanwhile, the prediction methods are the most important factors for the prediction accuracy. Backfill-strip mining technology can be used to excavate coal resources under important buildings because it efficiently controls subsidence (Zhu et al. 2015). However, important buildings are sensitive to ground deformation, and even a small deformation can result in damage to buildings, which might cause a negative influence for society. So, the accuracy of backfill-strip mining subsidence prediction is significant to control building deformation and reduce mining damage.

In this paper, the superposition prediction method for backfill-strip mining was established based on the probability integral prediction model. This paper is organized as follows: Section 2 describes the conventional prediction methods for surface subsidence in backfill-strip mining. Section 3 presents a new prediction method proposed by this paper and the parameter selection principle of the prediction method. Section 4 uses the subsidence monitoring data of the similar material model and the numerical simulation model to verify the correctness of this prediction model, and a comparison between the conventional and the superposition prediction model is analyzed. Section 5 presents the conclusions.

Conventional prediction methods for surface subsidence in backfill-strip mining

Backfill-strip mining technology is composed of backfill mining technology and caving mining technology,and a conventional subsidence prediction method, which has been proposed based on the implementation process of backfill-strip mining technology, has been used to predict the surface subsidence in backfill-strip mining (Wang et al. 2015; Zhang et al. 2017; Dong et al. 2018). The calculation steps for this conventional prediction method are as follows: the backfill-strip mining area is divided into several small caving mining working faces and backfill working faces from the transverse perspective (Fig. 2). Then, the appropriate prediction parameters are chosen, and the surface subsidence caused by these small working faces predicted separately based on the probability integral method. Finally, the surface subsidence value of several small caving mining working faces and backfill working faces are added together. The sum value is the surface subsidence prediction result of the backfill-strip mining (Fig. 3).

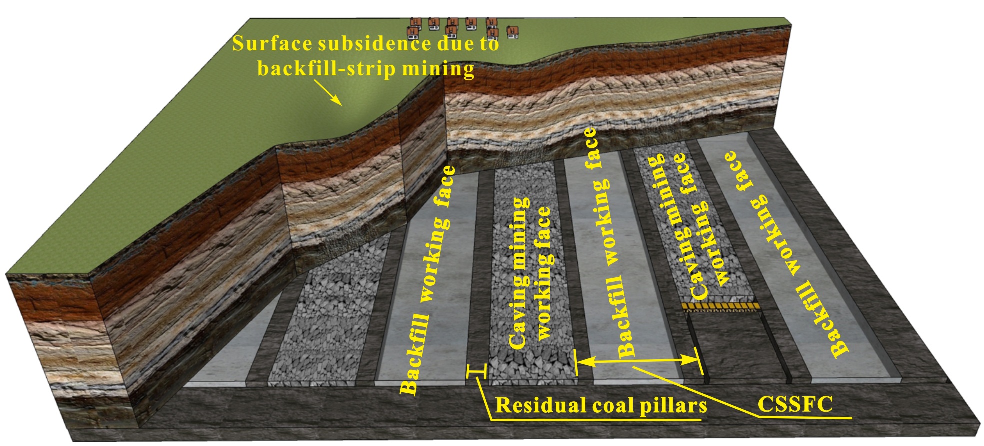

Fig. 1 Schematic of backfill-strip mining

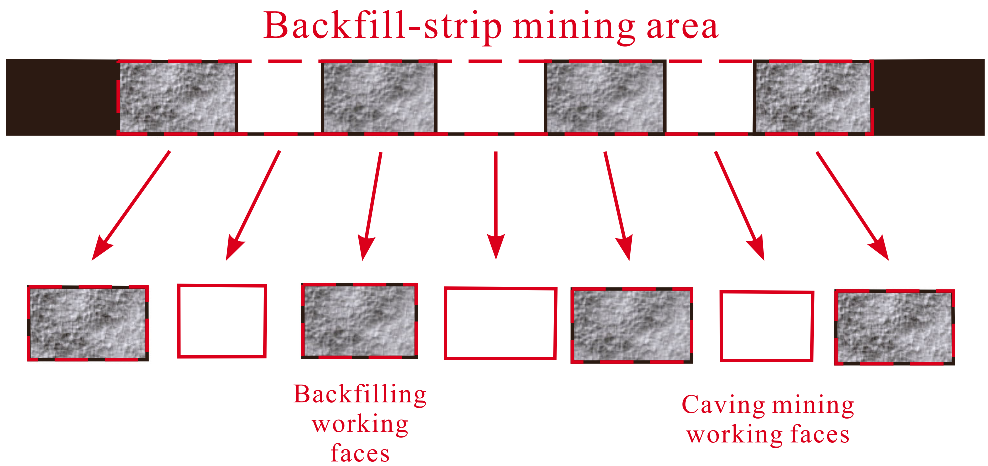

Fig. 2 Section schematic of the actual subsidence space of backfill-strip mining in the conventional method

This conventional prediction method can be easily implemented in computer programming and be applied for different geological mining conditions. However, the prediction parameters of this method are hard to determine accurately because the width of the working faces is small and cannot reach the critical mining size. These prediction parameters need to be modified based on the coefficient of mining degree (Wu et al. 1998; Zhai et al. 2012). However, the study of the parameter correction method is insufficient and the accuracy of the final subsidence prediction is low (Guo et al. 2004a, b). Meanwhile, the deformation characteristics of strata movement and the subsidence control mechanism of backfill-strip mining are different from those of other mining methods because the combined forms of the overlying strata, filling body, and coal pillars are specific (Zhu et al. 2018). Thus, the surface subsidence prediction of backfill-strip mining cannot directly use the prediction method of caving mining or backfill mining.

Therefore, the conventional subsidence prediction model of backfill-strip mining needs to be improved. An improved surface subsidence prediction method of backfill-strip mining is proposed in this paper based on the released process of actual subsidence space and so solving the problem of difficult parameter selection.

A superposition surface subsidence prediction method and parameter selection

The superposition surface subsidence prediction method

From the formation process of surface subsidence, the subsidence gradually spreads in the vertical direction from the goaf to the surface when coal is excavated. Finally, a subsidence basin on the surface is formed, and its extent is greater than that of the goaf. The difference in surface subsidence formed between varying mining methods is caused by the difference of the actual subsidence space and its location. The actual subsidence space of backfill-strip mining is released from the exploitation space of coal seams except for the space occupied by filling material (Zhu et al. 2018). This subsidence space consists of two parts, from top to bottom (Fig. 4). The upper part is released from the compressive deformation of the filling material during the backfill mining stage, and the bottom part is released from the roof caving during the caving mining stage.

From this perspective of the release process of the actual subsidence space, a superposition surface subsidence prediction method is proposed. The subsidence space of backfill-strip mining can be regarded as the superposition

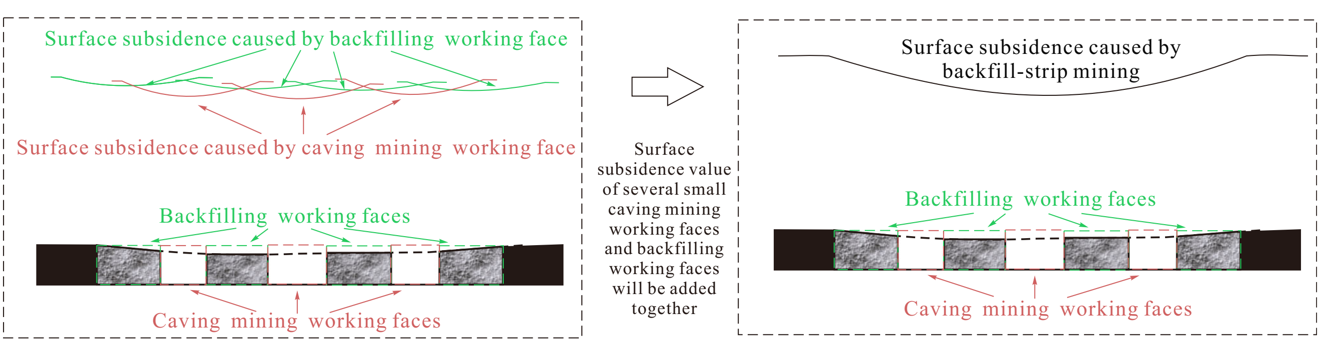

Fig. 3 The sum of the surface subsidence value of every working face in the conventional method

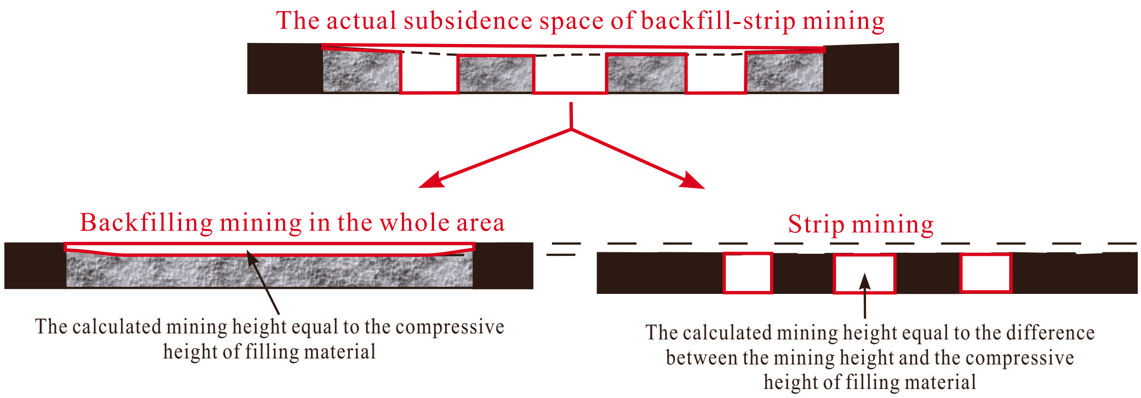

Fig. 4 Section schematic of the actual subsidence space of backfill-strip mining

of the subsidence space of the backfill mining and the strip mining in the whole area (Fig. 4). Meanwhile, the actual mining height of the backfill mining in the whole area is equivalent to the compressive height of the filling material, and the actual mining height of the strip mining is equivalent to the difference between the mining height and the compressive height of the filling material. Then, the surface subsidence caused by the hypothetical subsidence space of the backfill-strip mining and the strip mining can be separately predicted by the probability integral method. The calculation formula of this superposition prediction method based on the probability integral method is described in Section 3.1.1–3.1.4. The selection principle of the prediction parameters has been shown in Section 3.2. Finally, the surface subsidence of the backfill-strip mining is the sum of the two prediction results.

Brief overview on the probability integral method

The superposition surface subsidence prediction method for backfill-strip mining is developed on the basis of the probability integral method (Cui and Deng 2017), which is an influence function method, based on the extraction of the infinitesimal elements of an area. It is also one of the most widely applied methods for subsidence prediction of mining areas in China.

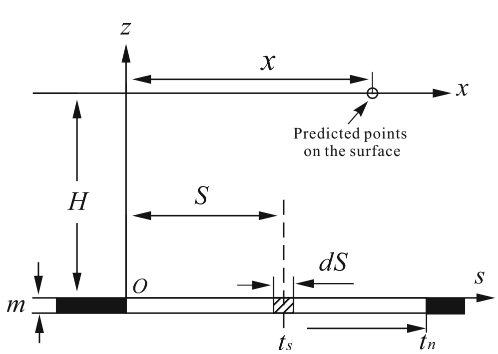

Fig. 5 Schematic of calculation of surface movement and deformation

In Fig. 5, assuming that the inclined width of the working face has reached a critical size, the mining thickness is M, and the depth is H. The original point of the coordinate system is s and z is located directly above the coal wall, and x is the horizontal distance of a monitored point on the surface with respect to the coal wall. The working face advances along the positive direction of the s axis.

The extraction of a unit area of coal seam causes the surface to subside as follows:

$$W_e(x) = \frac{1}{r} e^{-\frac{\pi x^2}{r^2}}. \quad (1)$$

Integrating the whole mining space, the formula for surface subsidence of any point is as follows:

$$W(x,y) = \frac{Mq\cos\alpha}{r^2} \int_0^{D_3} \int_0^{D_1} e^{-\pi\frac{(x-s)^2+(y-t)^2}{r^2}} dtds, \quad (2)$$

where $W(x, y)$ is the subsidence at the surface point with coordinates x and y, M is the mining height, α is the seam inclination, r is the radius of major influence ($r = H/\tan\beta$), and D_3 and D_1 are the computed width and length of the panel, respectively. The five prediction parameters of this method are the subsidence coefficient (q), horizontal displacement coefficient (b), tangent of major influence angle ($\tan\beta$), offset of inflection point (s), and main propagation angle (θ).

Surface subsidence caused by backfill-strip mining can be regarded as the superposition of the influence of backfill mining and strip mining (Fig. 6).

Surface subsidence of backfill mining and strip mining can be calculated by using the principle of the following two subsidence prediction methods based on the probability integral method.

Surface subsidence prediction of the backfill mining

The surface subsidence and strata deformation processes of the backfill mining differ from those of caving mining. The

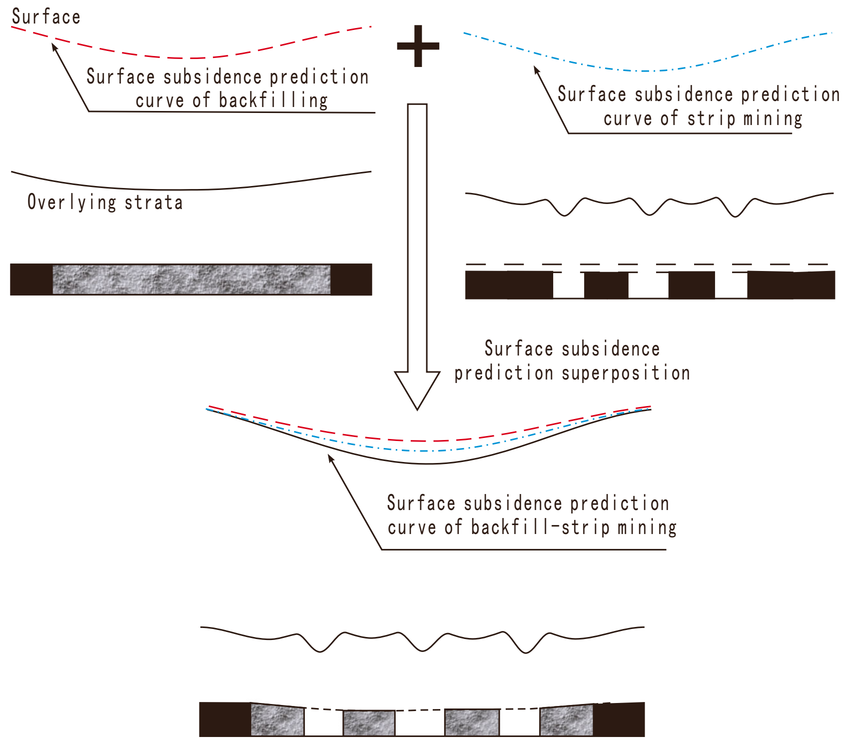

Fig. 6 The superposition prediction method based on the probability integral method

backfill materials in backfill mining are initially loose when they are used to fill in goaf and are then rapidly compressed to achieve compaction under the roof pressure. The thickness of the backfill mining is not the thickness of the coal seam, and the traditional probability integral prediction model of caving mining cannot be applied in backfill mining. To solve this problem, Guo et al. (2014) proposed the concept of equivalent mining height in solid backfill mining and assumed that the subsidence basin induced by solid backfill mining is the same as the deformation caused by caving mining with an equivalent height (Fig. 7). The equivalent mining height is the difference between the actual mining height of the filling working face and the compaction of the solid filling material in the mined-out area; that is, the equivalent mining height is the mining height of the working face minus the height of the filling material after compaction. Therefore, the subsidence induced by backfill mining can be converted to predict the deformation induced by caving mining. The surface subsidence prediction of backfill mining in the entire area can be calculated by using the probability integral method based on equivalent mining height.

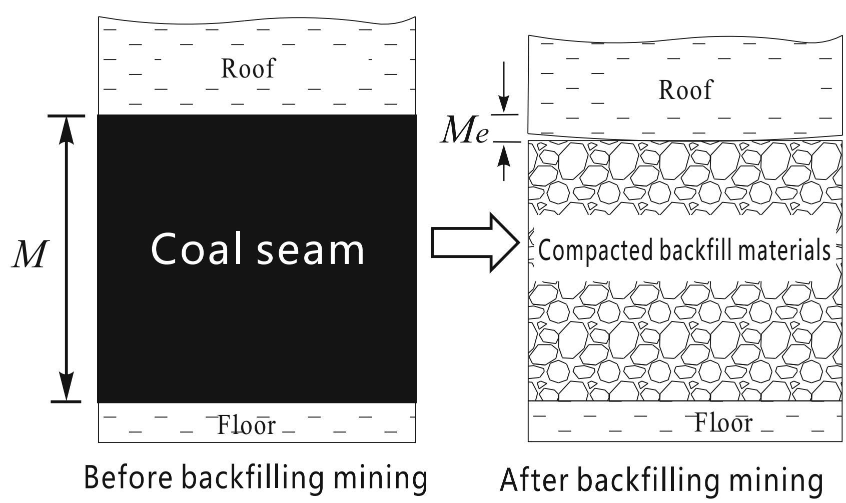

Fig. 7 Equivalent height mining

The equivalent mining height can be computed by Eq. (3):

$$M_e = (M-\delta-\Delta)\eta + \delta + \Delta, \quad (3)$$

where M_e is the equivalent mining height, δ is the initial roof displacement, Δ is the unfilled height in the goaf, and η is the compression rate of the filling body.

Substituting the equivalent mining height Eq. (3) into Eq. (2), the surface subsidence of backfill mining can be calculated as follows:

$$W_b(x,y) = [(M-\delta-\Delta)\eta + \delta + \Delta]q_b\cos\alpha \iint_D \frac{1}{r_b{}^2} e^{-\pi\frac{(\eta-x)^2+(\xi-y)^2}{r_b{}^2}} d\eta d\xi, \quad (4)$$

where $W_b(x, y)$ is the surface subsidence of the point in (x, y), q_b is the subsidence coefficient in backfill mining and a prediction parameter of the probability integral method, r_b is the radius of major influence in backfill mining and is equal to $H_0/\tan\beta_b$, H_0 is the average mining depth, and $\tan\beta_b$ is the tangent of the major influence angle and also a prediction parameter of the probability integral method.

Surface subsidence prediction of strip mining

The mining thickness of strip mining is that of the original coal seam minus the roof subsidence value after the mining stabilizes. The calculated mining height of strip mining M_s can be computed by using Eq. (5):

$$M_s = M-M_e = (M-\delta-\Delta)(1-\eta). \quad (5)$$

The coal pillar width of strip mining is the sum of the width of the coal pillars and the backfill working face in backfill-strip mining. The mining width of strip mining is the same as that of the caving mining working face during backfill-strip mining. The surface subsidence of strip mining can be calculated by Eq. (6):

$$W_s(x,y) = (M-\delta-\Delta)(1-\eta)q_s\cos\alpha \iint_D \frac{1}{r_s{}^2} e^{-\pi\frac{(\eta-x)^2+(\xi-y)^2}{r_s{}^2}} d\eta d\xi, \quad (6)$$

where $W_s(x, y)$ is the surface subsidence of the point in (x, y) caused by the strip mining, q_s is the subsidence coefficient in strip mining, and r_s is the radius of major influence in backfilling mining.

Surface subsidence superposition prediction of backfill-strip mining

Surface subsidence of backfill-strip mining can be regarded as the sum of the surface subsidence of backfilling and strip mining (Fig. 6). A surface subsidence prediction model of backfill-strip mining can be established in accordance with the superposition principle. This model is referred to as a superposition prediction method based on the probability integral method, and its surface subsidence value includes two parts:

$$W = W_b + W_s = [(M-\delta-\Delta)\eta + \delta + \Delta]q_b\cos\alpha \iint_D \frac{1}{r_b{}^2} e^{-\pi\frac{(\eta-x)^2+(\xi-y)^2}{r_b{}^2}} d\eta d\xi + (M-\delta-\Delta)(1-\eta)q_s\cos\alpha \iint_D \frac{1}{r_s{}^2} e^{-\pi\frac{(\eta-x)^2+(\xi-y)^2}{r_s{}^2}} d\eta d\xi. \quad (7)$$

Determination of parameters of the superposition subsidence prediction model

The superposition subsidence prediction model is established on the basis of the probability integral method. Thus, the superposition subsidence prediction model consists of the same five subsidence prediction parameters: subsidence coefficient q, horizontal movement coefficient b, tangent of major influence angle $\tan\beta$, offset of the inflection point S, and main propagation angle θ. The measured data of surface subsidence are inadequate for backfill-strip mining. Thus, obtaining parameters directly from the measured data is infeasible. Backfill-strip mining combines the advantages of backfilling mining and strip mining. Researchers have conducted many field observations in China for backfill mining and strip mining. Thus, numerous parameters for the probability integral method have been obtained. The superposition subsidence prediction model of backfill-strip mining can use the parameter selection principle of backfill mining and strip mining for reference.

Parameter selection principle of backfilling mining

Guo et al. (2014) analyzed the parameters of the probability integral method based on equivalent mining height of backfilling in accordance with theoretical research and the results of similar material simulations. A slight difference is observed between the parameters of backfill mining and those of caving mining with the same mining height. The parameters are described below.

(1) The subsidence coefficient q_b in the backfill mining is nearly equal to that in thin-seam caving mining, which has the same mining height as the equivalent mining height of backfill mining. Thus, q_b in solid backfill mining can be determined with reference to the subsidence coefficient in thin-seam caving mining.

(2) The tangent of major influence angle tan β_b is used to assess the range of the surface subsidence basin. The tan β_b is smaller than that of thin-seam caving mining under similar geological conditions from 0.2 to 0.5. In general, tan β_b ranges from 1.2 to 1.6.

(3) The main propagation angle θ is used to specify the distance of the inflection point toward the lower side of the panel and depends on the angle of the seam inclination. θ_b in backfill mining is slightly smaller than θ for caving mining under similar geological conditions.

(4) The offset of the inflection point is denoted by S. During caving mining, cantilevers form on the boundary of the goaf, and thus reduce the actual subsidence space for collapsed strata. Therefore, the inflection point is introduced in the prediction method to correct the computed size of the goaf. For backfill mining, the equivalent mining height is the virtual height, and the overburden strata supported by the filling material is difficult to break. Thus, S_b in backfill mining does not relate to the characteristics of S in caving mining. From a security standpoint, the offset of the inflection point can be set to 0 in the subsidence prediction of backfill mining.

(5) The horizontal movement coefficient b is the ratio between the maximum horizontal and vertical movement. b_b of the backfill mining is the same as b of caving mining.

Parameter selection principle of strip mining

The probability integration method can still be applied in the surface subsidence prediction of strip mining and is divided into two classes.

When the number of the strips in strip mining is few or the shapes of the strip mining working face are irregular, every working face of the strip mining can be considered a super-subcritical working face. The surface prediction subsidence of the strip mining is equal to the superposition prediction subsidence of all the super-subcritical working faces. For the prediction parameters of the super-subcritical working face, we can refer to those of the probability integration method of caving mining.

When the shapes of the strips and coal pillars are regular and the mining area is large, the entire strip mining area, including coal pillars, is considered the mining scope for predicting surface subsidence, and its parameters are revised on the basis of the probability integral method parameters of caving mining.

For the second case, the empirical formulae of the prediction parameters are established by scholars on the basis of a large amount of measured and numerical simulation data on strip mining. Guo et al. (2005) established the predicting parameter relationship between the strip mining and caving mining methods based on a large amount of field measured data (Table 1).

Verification of surface subsidence prediction method

Backfill-strip mining technology is still in the industrial test stage and has not been widely applied. Thus, the surface subsidence data of the similar material and the numerical simulation models are applied to verify the feasibility and accuracy of the superposition prediction method for backfill-strip mining in this study.

Numerical simulation experiment

The numerical simulation analysis software, Flac3d, has been adopted to verify the feasibility of the subsidence superposition method and the correctness of subsidence prediction method in backfill-strip mining. Yangzhuang coal mine, which is located in Huaibei City, Anhui Province, China, has been selected as the verification case in this study. Numerous residential buildings are located above this mining area. Statistics indicate that the estimated recoverable coal reserves under the residential buildings are 20.8 million tons, thereby severely limiting the active period of the coal mine. In the original design of the coal mine, backfill mining was

Table 1 Parameters of probability integral method in strip mining

Prediction parameters	Formulae
q_s	$\frac{q_s}{q} = 0.2663e^{-0.5753M}\rho^{2.6887}\ln\left(\frac{bH}{a}\right) + 0.0336$
b_s	$\frac{b_s}{b} = -0.0002\frac{H(a+b)}{b} + 0.8786$
$\tan\beta_s$	$\frac{\tan\beta_s}{\tan\beta} = 0.7847e^{-0.0012PH}$
S_s	$S_s = 0.0673\frac{b^2H}{a(a+b)} + 2.564$

ρ is the mining rate, b is the mining width, and a is the retaining width of the coal pillar. q_s, b_s, tan β_s, and S_s are the prediction parameters of strip mining. q, b, tan β, and S are the prediction parameters of caving mining.

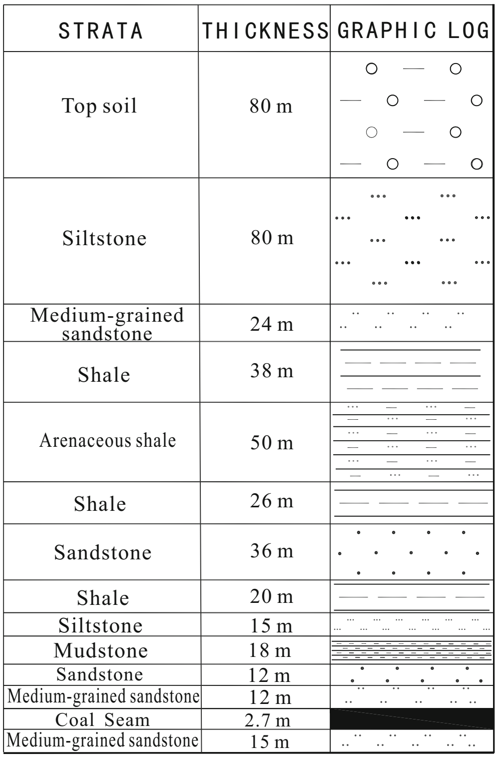

Fig. 8 Simplified geological stratum diagram

applied to exploit the coal seam under the buildings and prevent damage to them. However, the filling cost is relatively high. Relocating the buildings above the mining area would be costly. Therefore, backfill-strip mining has been used to extract the coal resources under the buildings and so reduce the filling cost.

The simulated structure of the overlying strata is appropriately simplified on the basis of the actual site situation and test conditions. The graphic log of the simplified strata structure is shown in Fig. 8. The immediate roof and the floor are made of medium-grained sandstone, and the No. 6 coal seam, with an average thickness of 2.7 m and an average depth of 400 m, has been used to simulate the excavation. The model has a size of 1600 m × 1600 m and is divided into 294,400 units. The panels extract coal from the No. 6 coal seam with an average thickness of 2.7 m and an average depth of 400 m. Five backfilli working faces with a size of 60 m × 600 m and four caving mining working faces with a size of 60 m × 600 m are simulated. The coal pillars with a width of 10 m are retained. The horizontal displacement is fixed along the boundaries of the model, and horizontal and vertical displacements are fixed along the bottom. However, the top is a free surface. The surrounding rock is isotropic medium, and the reactions between the strata are superimposed by their own gravity. The Mohr–Coulomb model is adopted for the overlying strata, coal seam, and filling body. Figure 9 shows the simulation model. Table 2 shows the mechanical parameters of strata, coal, and filling body, which are calibrated in accordance with the surrounding rock conditions and the field-measured subsidence data in caving mining. The surface subsidence value is calculated by the numerical model.

To verify the superposition prediction method for backfill-strip mining, the surface prediction result by the prediction method in this study, the conventional prediction method and the simulation results have been compared. In the subsidence prediction process of backfill-strip mining, the prediction parameters of backfilling mining refer to the corresponding parameters of the thin-seam longwall caving mining. The subsidence coefficient q_b is 0.9, the horizontal movement coefficient b_b is 0.35, the tangent of major influence angle $\tan\beta_b$ is 1.8, and the offset of the inflection point S_b is 0 m. These values were selected by consulting the measured parameters of an adjacent caving working face in the Yangzhuang coal mine.

Strip mining involves few strips. Thus, the mining area can be considered to have three caving working faces. The prediction parameters should be modified in accordance with the mining degree coefficient (China National Bureau of Coal Industry 2017). The subsidence coefficient q_s is 0.49, the horizontal movement coefficient b_s is 0.35, the tangent of major influence angle $\tan\beta_s$ is 1, and the offset of the inflection point S_s is 0 m.

The prediction results of surface subsidence in the inclined main section obtained by this paper's method and the conventional prediction method, and the final subsidence results

Fig. 9 Numerical simulation model

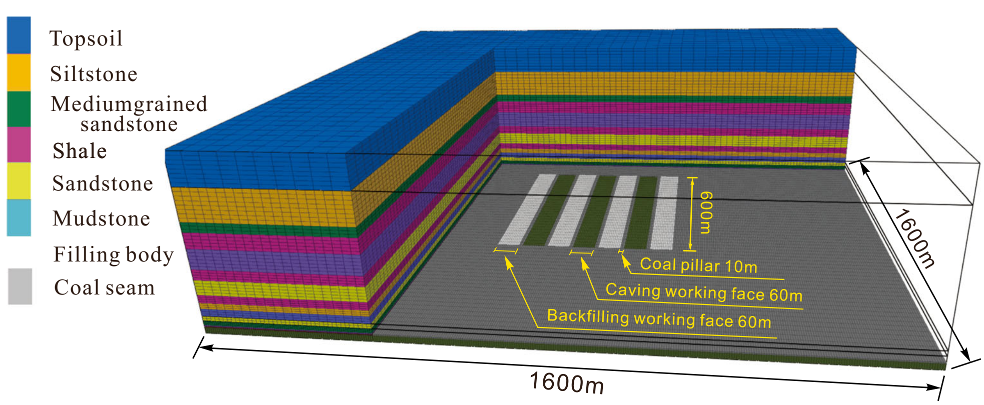

Table 2 Mechanical parameters of rock strata in simulation

Rock mass	Thickness (m)	Density (kg·m^{-3})	Bulk modulus (GPa)	Shear modulus (GPa)	Angle of internal friction (°)	Cohesion (MPa)
Topsoil	80	1800	0.03	0.03	10	0.02
Siltstone	80	2453	4.27	2.56	39	3.47
Medium grained sandstone	24	2484	8.20	4.92	37	3.4
Shale	38	2400	6.67	3.26	39	2
Arenaceous shale	50	2408	5.83	3.67	39	3.48
Shale	26	2400	6.67	3.26	39	2
Sandstone	36	2842	5.78	4.33	37	3.8
Shale	20	2400	6.67	3.26	39	2
Siltstone	15	2453	4.27	2.56	39	3.47
Mudstone	18	2410	4.21	2.87	30	3.8
Sandstone	12	2842	5.78	4.33	37	4.5
Medium grained sandstone	12	2484	8.20	4.92	37	3.4
Coal seam	2.7	1400	2.17	1.00	25	0.55
Medium grained sandstone	15	2484	8.20	4.92	37	3.4

obtained from the numerical model, have been compared. The comparison curves are shown in Fig. 10.

The comparison shows that the predicted subsidence curve by this study's prediction method is close to the simulated one The maximum prediction subsidence value is 700 mm, which is 25 mm greater than the simulation subsidence value in the center of the subsidence basin, and the predicted subsidence values are smaller than the simulated subsidence value at the edge of the subsidence basin. Every prediction subsidence value has been compared with the simulation subsidence result. The mean square error is 40 mm according to the formula $m = \pm\sqrt{\Delta\Delta/n}$ where Δ is the difference between the predicted subsidence value and the simulated subsidence value, n is the number of prediction points, and the relative error is 5.7%. However, the predicted subsidence curve by this conventional prediction method is different from the simulation subsidence curve. The maximum predicted subsidence value is 159 mm smaller than that of the numerical simulation. The mean square error is 89 mm and the relative error is 17.1%.

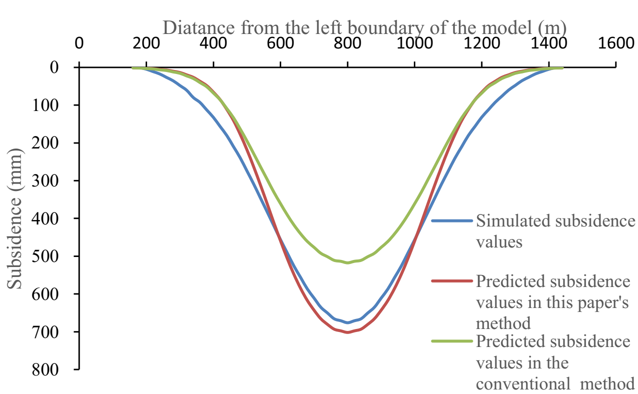

Fig. 10 Contrast analysis diagram of the predicted and simulated subsidence values

Similar material modeling experiment

Similar material modeling (Mitchell et al. 1983; Peng 2013) is one of the most effective methods for studying ground and strata destruction induced by underground coal exploitation. A similar material scale model is constructed by using simulation material on the basis of scale model theory. The model can realistically simulate surface subsidence and overlying strata movement processes, much like that observed in underground coal mines. The strata movement data of the model were measured and converted into actual values for comparative and critical analysis (Gao et al. 2008). This simulation method is easier and faster than field measurements and can compensate for the limitations of field measurements with its advantages of short experimental period, low cost, and visual results.

Geological and mining conditions simulated by the similar material model are the same as those by the above numerical model. However, the similar material model only simulates the two-dimensional displacement and deformation of strata in backfill–strip mining along the direction of the dip section, under the assumption that the strike length of the working faces has reached a critical size. The actual widths of the backfilling working face, caving mining working face, and barrier pillar are 60, 60, and 10 m, respectively. The simulation mining process of the model can be divided into two stages. In Stage I, the similar material model adopts backfill mining from left to right, with each working face being filled immediately after being mined. In Stage II, residual pillars are mined using caving mining after Stage I, and 10-m-wide

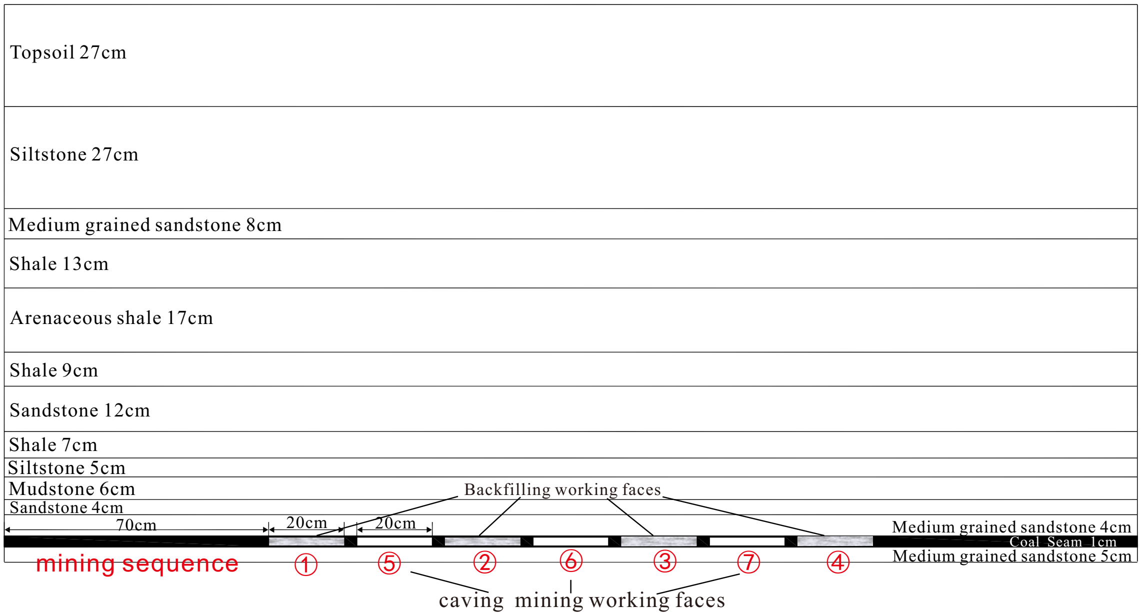

Fig. 11 Design chart of the similar material model

barrier pillars are reserved between the caving mining and backfill working faces (Fig. 11).

On the basis of the simulation stratum diagram and experimental conditions, an experimental modeling with the similar materials has ben conducted on iron shelves with dimensions of 300 mm × 300 mm × 1400 m (length, width, and height). In reflecting the important physical properties of the prototype (e.g., mechanical and kinetic characteristics), the similar material model and the actual geological environment must follow three similarity theorems (Ghabraie et al. 2015), namely, geometric similarity, kinematic similarity, and mechanical similarity, to ensure that the physical model is proportional to the prototype system. In accordance with the simulation mining scope and the sizes of the panel shelves, the geometric similarity ratio of model α_l is set to 1:300, and the time similarity ratio is $c_t = \sqrt{c_l} = 17.3$. The similar

Table 3 Mechanical parameters of the model

Rock type	Prototype parameters			Model parameters		
	Thickness (m)	Compressive strength (MPa)	Tensile strength (MPa)	Thickness (cm)	Compressive strength (MPa)	Tensile strength (MPa)
Topsoil	80	3.26	0.40	27	0.0068	0.0008
Siltstone	80	35.87	2.80	27	0.0747	0.0058
Medium grained sandstone	24	40.36	1.40	8	0.0841	0.0029
Shale	38	18.60	0.98	13	0.0388	0.0020
Arenaceous shale	50	26.47	0.9	17	0.0551	0.0019
Shale	26	18.60	0.98	9	0.0388	0.0020
Sandstone	36	42.50	1.40	12	0.0885	0.0029
Shale	20	18.60	0.98	7	0.0388	0.0020
Siltstone	15	35.87	2.80	5	0.0747	0.0058
Mudstone	18	10.44	0.80	6	0.0218	0.0017
Sandstone	12	42.50	1.40	4	0.0885	0.0029
Medium grained sandstone	12	30.36	0.84	4	0.0633	0.0018
Coal	2.7	11.50	0.60	1	0.0240	0.0013
Medium grained sandstone	15	52.50	1.80	5	0.1094	0.0038

Table 4 Similar material proportion of the model

Rock type	Material proportioning			
	Sand (%)	Mica powder (%)	Plaster (%)	Calcium carbonate (%)
Topsoil	94	4	0.6	1.4
Siltstone	93	4	2.1	0.9
Medium grained sandstone	92	4	2.8	1.2
Shale	92	5	1.2	1.8
Arenaceous shale	93	4	1.5	1.5
Shale	92	5	1.2	1.8
Sandstone	92	4	2.8	1.2
Shale	92	5	1.2	1.8
Siltstone	92	4	2.4	2.4
Mudstone	91	6	1.8	2.1
Sandstone	92	4	2.8	1.2
Medium grained sandstone	93	4	1.5	1.5
Coal	93	4	2.1	0.9
Medium grained sandstone	89	3	5.6	2.4

material is composed primarily of sand and has a density of 1500 kg/m^3. Thus, the density similarity ratio c_ρ = 1:1.6, and the mechanical similarity ratio c_δ is 1:480. Mechanical parameters of the model are determined (Table 3) on the basis of the strength parameters of the various strata and the similarity ratio.

The similar materials used in the model are compounds and mainly composed of dry sand, mica powder, plaster, light calcium carbonate, and water. The different compressive strength and tensile strength of the similar materials can be obtained by changing the proportioning of these raw materials. According to the calculation of mechanical parameters of the model and the empirical formula of the tensile and compressive strengths of the different similar material proportion in reference literature, the dosage of various kinds of materials can be calculated (Table 4).

In obtaining the surface subsidence of the similar material model of backfill-strip mining, a digital close-range photogrammetry system (Zhang 2010) has been used to monitor the surface subsidence of the similar material model of backfill-strip mining (Fig. 12). The monitoring accuracy of this system is 0.03–0.1 mm. The actual monitoring accuracy is 9–30 mm, which can be calculated in accordance with the 1:300 geometric similarity ratio. The monitoring points in this model can be divided into two classes, namely, code and non-code marked points. The code marked points are pasted with a certain density distribution on the surface of the model for a multiple image mosaic. The non-code marked points are pasted to monitor the

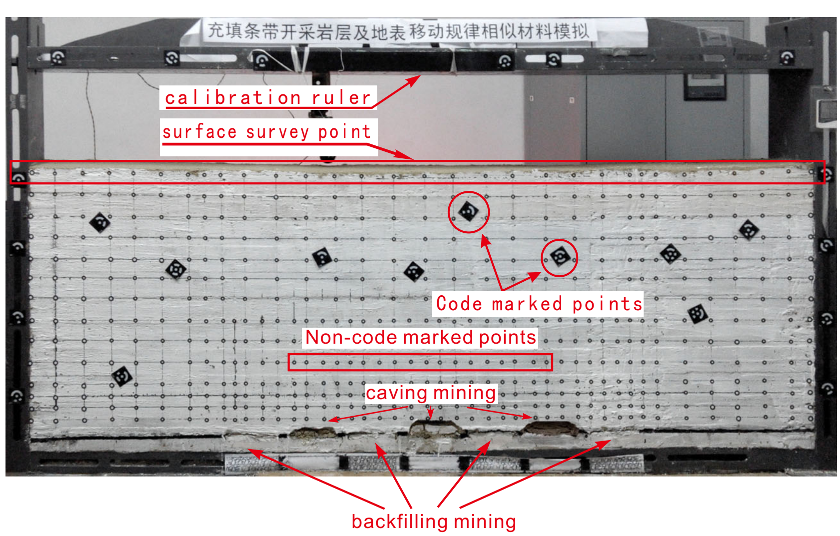

Fig. 12 Layout of the model monitoring points for close-range photogrammetry system

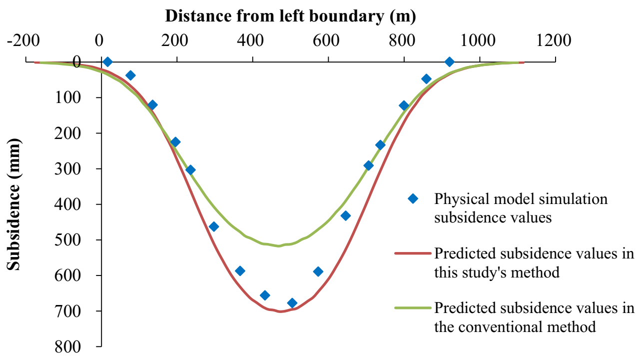

Fig. 13 Contrast analysis diagram of the prediction values and similar material model simulation values

displacement of the survey points. The final surface subsidence of the backfill-strip mining can be obtained by calculating the position difference of the surface survey points before and after the similar material model excavation.

Similarly, the simulation results of the similar material model were compared with the surface prediction result by the prediction method in this study to verify the prediction method for backfill-strip mining. The subsidence prediction parameters selected here were the same as that in Section 4.1, because the two verifications are performed under the same geological and mining conditions. The subsidence coefficient q_s is 0.4, the horizontal movement coefficient b_s is 0.35, the tangent of major influence angle $\tan\beta_s$ is 1, and the offset of the inflection point S_s is 0 m.

The prediction results of surface subsidence in the inclined main section obtained by the prediction method in this study, the conventional prediction method and the final subsidence results obtained from the similar material model have been compared. The comparison curves are shown in Fig. 13.

The comparison shows that the predicted results in backfill-strip mining are slightly greater than the similar material simulation results, and the range of the subsidence basin of the predicted results is wider. The maximum predicted subsidence value is 17 mm greater than that of the similar material simulation. The subsidence value of each monitoring point in the similar material model is compared with the predicted result in this study's method: the MSE is 47 mm, and the RE is 6.7%. The predicted subsidence curve by this paper's prediction method is different from the subsidence curve obtained by the similar material model. The maximum predicted subsidence value is 166 mm smaller than that of the similar material model: the MSE is 74 mm and the RE is 10.6%.

Discussion

The backfill–strip mining method is proposed on the basis of the "three-step" mining subsidence control (Guo et al. 2004a, b) to solve the problems of high backfill costs and backfill material shortage. Although backfill-strip mining is a partial filling mining method, it is different from backfill mining. First, the backfill-strip mining is composed of backfill mining working faces and caving mining working faces (Fig. 1). The mining technology of the backfill-strip mining is different from that of the backfill mining. Second, some scholars have studied the strata movement process and the surface subsidence characteristics of the backfill mining and backfill-strip mining based on the field-measured data and simulation data (Guo et al. 2014; Zhu et al. 2018). The result shows that there is a great difference between the strata structural process and surface subsidence characteristics movement process in the backfill-strip mining and backfill coal mining. Thus, the surface subsidence prediction method and the subsidence monitoring data of the backfill mining are not very suitable for backfill-strip mining. The superposition prediction method is proposed in this paper in order to provide a scientific design reference for backfill-strip mining.

As backfill-strip mining technology is still in the industrial test stage and has not been widely applied, no suitable field data can be used to verify the prediction model of the backfill-strip mining. To verify the feasibility and accuracy of the superposition prediction method for backfill-strip mining, the surface subsidence data of the numerical simulation and the similar material models have been obtained. Comparing the two kinds of predicted results and the two kinds of simulation results, the prediction subsidence results predicted by this study's superposition method are close to the results of the simulation experiments: the mean square errors are 40 mm and 47 mm, and the relative errors are 5.7% and 6.7%, respectively (Table 5). However, the results of the conventional prediction method are very different from the results of the simulation experiments: the mean square errors are 89 mm and 74 mm, and the relative errors are 17.1% and 10.6%, respectively. It can be seen from the above data that the average prediction error of this superposition prediction method is less

Table 5 Errors between the two kinds of predicted results and the two kinds of simulation results

	Superposition prediction method		Conventional prediction method	
	Mean square error	Relative error	Mean square error	Relative error
Numerical simulation result	40 mm	5.7%	89 mm	17.1%
Similar material model result	47 mm	6.7%	74 mm	10.6%

than 6.7% and its prediction accuracy is 3.9%~11.4% higher than that of the conventional prediction method.

Why is there a difference in the prediction accuracy of the two methods? We suspect that the difference in the division form of the subsidence space between the two methods results in a different accuracy of the prediction parameters and results. The excavation scope of backfill-strip mining is sufficiently large and reaches critical mining size. However, the conventional prediction method divides the entire mining area into several small working faces, which cannot reach critical mining size. Thus, the prediction parameters of the small working faces will be smaller than normal. In the superposition prediction method, the size of the actual subsidence space reaches critical mining size. Therefore, the superposition prediction method is more reasonable than the conventional prediction method.

Furthermore, there is a little difference between the superposition prediction and the simulation subsidence results. Two possible reasons can explain these differences. First, the prediction method of backfill-strip mining is proposed based on the traditional probability integral method prediction model. The integral method prediction model has a problem that the subsidence prediction value is relatively small at the edge of the subsidence basin (Wang et al. 2012), especially in thick alluvium coal mines. Second, the overlying strata in the numerical model and similar material model are equivalent to the continuum medium due to the limitation of the simulation method, whose mechanical behavior is different from that of the actual broken rock in the process of mining. So, the error of the mining subsidence value gradually forms in the process of simulation. Although a slight difference exists between the predicted and simulated subsidence results, the result predicted by the equivalent superposition probability integral method can satisfy the precision requirement of engineering applications (the relative errors are less than 10%) and thus is reasonable.

Consequently, the superposition surface subsidence prediction method is reasonable. Its accuracy is higher than that of the conventional prediction method and can satisfy the precision requirement of engineering applications.

Conclusion

To accurately predict the surface movement and deformation of backfill-strip mining, a superposition prediction model of backfill-strip mining is proposed based on the traditional probability integral method prediction model. In this method, the surface subsidence problem can be regarded as the superposition of the surface subsidence caused by backfill mining and strip mining. The similar material and the numerical simulation models have been built to verify the prediction accuracy of this method. The comparison results of the surface subsidence values show that the relative error of the superposition prediction method is less than 10%. Meanwhile, its accuracy is higher than that of the conventional prediction method and can satisfy the precision requirement of engineering applications. This prediction method provides a scientific technical reference for safe mining engineering design and surface disaster protection for backfill-strip mining.

Acknowledgements Financial support for this work, provided by the National Natural Science Foundation of China (51804001), the Key University Science Research Project of Anhui Province (KJ2017A038), Natural Science Foundation of Anhui Province (1808085QE147) and PhD Research Startup Foundation of Anhui University (J01003225) are gratefully acknowledged.

References

Abdelhadi K, Latifa O, Khadija B, Lahcen B (2016) Valorization of mining waste and tailings through paste backfilling solution, Imiter operation, Morocco. Int J Min Sci Technol 26(3):511–516

Bian ZF, Miao XX, Lei SG, Chen SE, Wang WF, Struthers S (2012) The challenges of reusing mining and mineral-processing wastes. Science 337(6095):702–703

Chen SJ, Guo WJ, Zhou H, Wen GH (2011) Structure model and movement law of overburden during strip pillar mining backfill with cream-body. J China Coal Soc 07:1081–1086 (in Chinese)

Chen SJ, Yin DW, Cao FW, Liu Y, Ren KQ (2016) An overview of integrated surface subsidence-reducing technology in mining areas of China. Nat Hazards 81(2):1129–1145

Chen Y, Zhang J, Zhou A, Yin B (2018) Modeling and analysis of mining subsidence disaster chains based on stochastic petri nets. Nat Hazards 6(1):1–23

China National Bureau of Coal Industry (2017) Rules for the mine extraction and coal pillars establishment under buildings, water bodies, railways and main laneways. China Coal Industry Press, Beijing (in Chinese)

Cui XM, Deng KZ (2017) Research review of predicting theory and method for coal mining subsidence. Coal Sci Technol 01:160–169 (in Chinese)

Dong X, Huang YC, Zhao WP, Liu G (2018) Research on safety of backfill mining strip pillars under villages. China Saf Sci J 28(8): 117–112 (in Chinese)

Gao F, Zhou KP, Dong WJ, Su JH (2008) Similar material simulation of time series system for induced caving of roof in continuous mining under backfill. J Cent S Univ Technol 15(3):356–360

Ghabraie B, Ren G, Zhang X, Smith J (2015) Physical modelling of subsidence from sequential extraction of partially overlapping longwall panels and study of substrata movement characteristics. Int J Coal Geol 140:71–83

Ghasemi E, Ataei M, Shahriar K (2014) An intelligent approach to predict pillar sizing in designing room and pillar coal mines. Int J Rock Mech Min 65(2):86–95

Guo GL, Wang YH, Ma ZG (2004a) A new method for ground subsidence control in coal mining. J China Univ Min Technol 33:150–153

Guo ZZ, Xie HP, Wang JZ (2004b) Applying probability distribution density function to predict the surface subsidence caused by subcritical extraction. J China Coal Soc 29(2):155–158 (in Chinese)

Guo WB, Deng KZ, Zou YF (2005) Research on surface movement parameters of strip-partial mining. J China Coal Soc 2:182–186 (in Chinese)

Guo GL, Feng WK, Zha JF, Liu YX, Wang Q (2011) Subsidence control and farmland conservation by solid backfilling mining technology. Trans Nonferrous Metals Soc S3(21):S665–S669

Guo GL, Zhu XJ, Zha JF (2014) Subsidence prediction method based on equivalent mining height theory for solid backfilling mining. Trans Nonferrous Metals Soc 24(10):3302–3308

Huang QX (2002) Ground pressure behavior and definition of shallow seams. Chin J Rock Mech Eng 21(8):1174–1177 (in Chinese)

Huang QX, Lai JQ (2016) Study on mechanical model of aquifuge beam supported by filling strip in the water preserved mining. J Min Saf Eng 33(04):592–596 (in Chinese)

Huang J, Tian CY, Xing LF, Bian ZF, Miao XX (2017) Green and sustainable mining: underground coal mine fully mechanized solid dense stowing-mining method. Sustainability-Basel 9(8):1–18

Lamich D, Marschalko M, Yilmaz I, Bednářová P, Niemiec D, Kubečka K, Mikulenka V (2016) Subsidence measurements in roads and implementation in land use plan optimisation in areas affected by deep coal mining. Environ Earth Sci 75(1):1–11

Mitchell RJ, Olsen RS, Smith JD (1983) Model studies on cemented tailings used in mine backfill. Int J Rock Mech Min 20(1):14–28

Peng SS (2013) Coal mine ground control. China University of Mining Technology Press, Xuzhou

Rošer J, Potočnik D, Vulić M (2018) Analysis of dynamic surface subsidence at the underground coal mining site in Velenje, Slovenia through modified sigmoidal function. Minerals-Basel 8(2):74

Salmia EF, Nazemb M, Karakusc M (2017) Numerical analysis of a large landslide induced by coal mining subsidence. Eng Geol 30(1):141–152

Wang N, Wu K, Qin ZF (2012) Prediction model of mining subsidence with probability integration method based on thickness influences of loose layer. Coal Sci Technol 40(7):10–16 (in Chinese)

Wang L, Li N, Zhang XN (2015) Surface subsidence quantitative control method of shallow buried coal mining with strip mining solid backfilling. Saf Coal Mines 46(11):31–34 (in Chinese)

Wu K, Ge JX, Zhou M, Yu FD (1998) Some modifications of using probability integral method to predicate model. J China Coal Soc 23(1):33–36 (in Chinese)

Xie WB, Shi ZF, Chen XX, Zheng BS (2004) Analysis of surrounding rock activities in partial backfill mining. J China Univ Min Technol 33(2):38–41 (in Chinese)

Xu JL, You Q, Zhu WB, Li XS, Lai WQ (2007) Theorectical study of strip-filling to control mining subsidence. J China Coal Soc 02:119–122 (in Chinese)

Zhai SC, Liu H, He CG (2012) Surface subsidence prediction of insufficiency mining based on probality integration method. Saf Coal Mines 43(06):29–31 (in Chinese)

Zhang D (2010) Exploitation of photogrammetry measurement system. Opt Eng 49(3):263–276

Zhang Q, Liu H, Zhai SC, Zheng LG, Chen YC (2017) Design and effect evaluation of the filling strip mining scheme under buildings. Metal Mine 496(10):105–109 (in Chinese)

Zhu XJ, Guo G, Qian Z, Fang Q (2015) Simulation analysis of strata movement characteristics of backfill-strip mining. J Mines Met Fuels 63(11):411–418

Zhu XJ, Guo GL, Zha JF, Chen T, Fang Q, Yang XY (2016) Surface dynamic subsidence prediction model of solid backfill mining. Environ Earth Sci 75(12):1–9

Zhu XJ, Guo GL, Liu H, Chen T, Yang XX (2018) Experimental research on strata movement characteristics of backfill–strip mining using similar material modeling. Bull Eng Geol Environ