Nat. Hazards Earth Syst. Sci., 16, 2473–2484, 2016
www.nat-hazards-earth-syst-sci.net/16/2473/2016/
doi:10.5194/nhess-16-2473-2016

Natural Hazards and Earth System Sciences
Open Access

Roadway backfill method to prevent geohazards induced by room and pillar mining: a case study in Changxing coal mine, China

Nan Zhou, Meng Li, Jixiong Zhang, and Rui Gao

Key Laboratory of Deep Coal Resource Mining, School of Mines, Ministry of Education of China, China University of Mining and Technology, Xuzhou 221116, China

Correspondence to: Meng Li (limeng1989@cumt.edu.cn)

Received: 3 May 2016 – Published in Nat. Hazards Earth Syst. Sci. Discuss.: 30 May 2016
Revised: 10 November 2016 – Accepted: 12 November 2016 – Published: 29 November 2016

Abstract. Coal mines in the western areas of China experience low mining rates and induce many geohazards when using the room and pillar mining method. In this research, we proposed a roadway backfill method during longwall mining to target these problems. We tested the mechanical properties of the backfill materials to determine a reasonable ratio of backfill materials for the driving roadway during longwall mining. We also introduced the roadway layout and the backfill mining technique required for this method. Based on the effects of the abutment stress from a single roadway driving task, we designed the distance between roadways and a driving and filling sequence for multiple-roadway driving. By doing so, we found the movement characteristics of the strata with quadratic stabilization for backfill mining during roadway driving. Based on this research, the driving and filling sequence of the 3101 working face in Changxing coal mine was optimized to avoid the superimposed influence of mining-induced stress. According to the analysis of the surface monitoring data, the accumulated maximum subsidence is 15 mm and the maximum horizontal deformation is $0.8\,\mathrm{mm\,m^{-1}}$, which indicated that the ground basically had no obvious deformation after the implementation of the roadway backfill method at 3101 working face.

1 Introduction

Recently, due to the high intensity and large scale of coal mining around the world, problems associated with resources and the environment have become more severe, and an increasing number of mining-induced hazards have been registered (Shi and Singh, 2001; Castellanza et al., 2010; Pasten et al., 2015; An et al., 2016; Zhai et al., 2016). The effects of these problems are especially prominent in the ecologically vulnerable areas of western China (Si et al., 2010; Ding et al., 2014). Many small and medium-sized coal mines in this area use room and pillar mining method and have a low mining rate (Jiang et al., 2015), leading to abandonment of the coal resources in underground. In addition, the burial depth of the coal seams in the region is usually shallower. During mining, geological behavior becomes more important, threatening mine production safety and usually causing unpredictable disasters, such as surface subsidence, landslides, and water inrush caused by karst environments (White, 2002; Vigna et al., 2010; Parise, 2012, 2015; Lollino et al., 2013). In particular, when karst caves are at shallow depth the effects at the ground surface may be extremely severe (Parise, 2008; Parise and Lollino, 2011), and the direct connection between the surface and the underlying karst aquifers usually functions as a channel for water inrush (Gutierrez et al., 2014), thus posing a great threat to coal mines. At present, previous studies proposed strip mining (Chen et al., 2012; Guo et al., 2014a) to resolve these problems. However, strip mining resulted in a low mining rate of coal resources as well as in other problems. To solve these difficulties, this research proposes roadway backfill technique in longwall mining based on the solid backfill mining method (Zhang et al., 2011; Junker and Witthaus, 2013; Guo et al., 2014b). This method has been recently developed and has become popular and applied at a large scale, providing an effective solution to the previously mentioned problems.

Recently, research into the strip filling method has promoted the development of the roadway filling method and its underlying theory (Zhang et al., 2007; Yu and Wang, 2011;

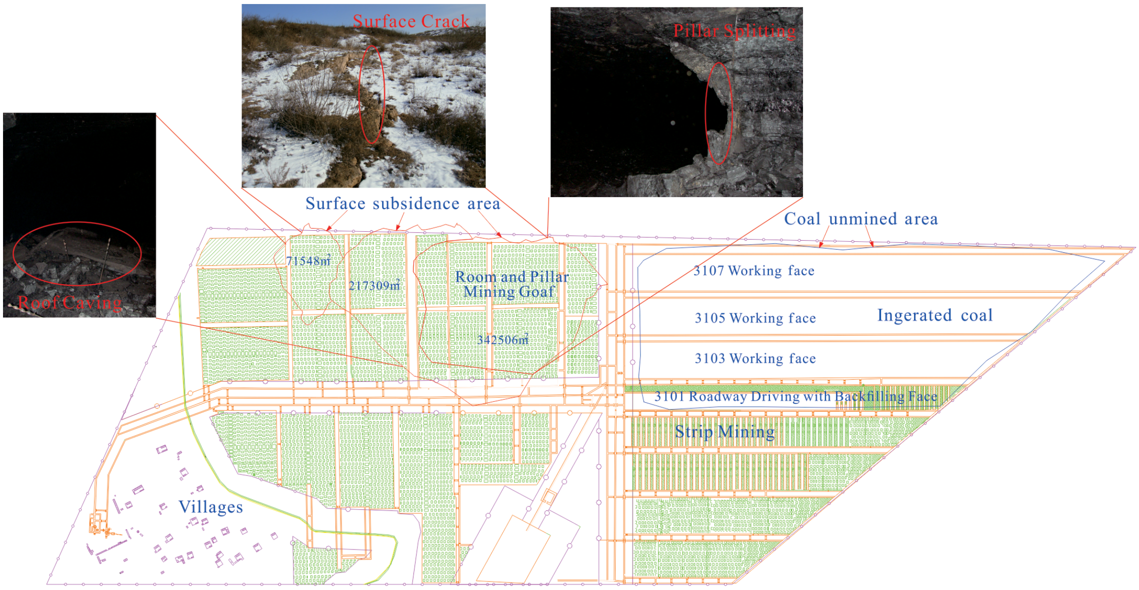

Figure 1. Surface subsidence induced by room and pillar mining and working face layout.

Chen et al., 2011; Sun and Wang, 2011), but few studies have been conducted on backfilling the driving roadway during longwall mining, especially from the perspective of the strata movement characteristics. Moreover, different types of backfill materials with different mechanical properties exist, and if the room and pillar mining method is adopted then strata behavior becomes the most important factor at shallow burial depths. Consequently, the characteristics of the strata movement in regions mined using this approach are significantly different from those in traditionally mined regions. The room and pillar mining method is normally used for shallow mines in western China to prevent the overlying strata from caving in and collapsing. A great quantity of coal resources is abandoned underground due to the use of the room and pillar method, which has caused a huge waste of coal resources. Additionally, the coal pillars creep over time and gradually fail (Bell and Bruyn, 1999; Castellanza et al., 2008). During pillar failure, the roof strata become fractured and the collapse progresses upwards (Ghasemi et al., 2012; Cui et al., 2014; Parise et al., 2015). Finally, surface subsidence results in building damage, environmental destruction, etc. The Changxing coal mine is used as a case study in this paper, and the roadway backfill method is proposed to solve the problems discussed above. We tested the mechanical properties of a backfill material composed of common aeolian sand, loess, and a cementing material. We also simulated strata movement characteristics with different roadway driving and filling sequences by FLAC$^{3\text{-D}}$ software. Finally, we used the research results to design the 3101 working face in the Changxing coal mine.

2 Geological and mining conditions

The Changxing coal mine, located about 15 km north of Yulin, Shaanxi Province, covers a field area of 4.82 km^2. The primary minable coal of the Changxing coal mine is the no. 3 coal seam, which has a stable horizon and simple structure. With a layer constituted of 0.09–0.60 m mudstone dirt band, this coal seam has an average thickness of 5.35 m and belongs to stable ultra-thick seam. From the southeast to northwest of the mine field, the burial depth gradually increases, and the coal seam slightly tilts to the northwest, with an average angle of about 0.5°. With an average burial depth of 130 m, the coal seam is the typical shallow-buried coal seam in the western area. The main roof is a medium-fine granular arkose, with thicknesses of 4.48–33.2 m; the immediate roof is silty mudstone; the main floor is siltstone with thickness of 0.10–9.28 m; and the coal seam floor has a simple structure, with a strong compressive strength, which will hardly cause floor heaving.

The room and pillar mining method was originally adopted in the Changxing coal mine, resulting in a mining rate of only 30 %. In addition, problems such as severe surface subsidence and significant coal loss caused by the instability of the mined rooms and coal pillars have threatened the mining field. Meanwhile, due to coal pillar failure, magnitude 2.5 and 2.8 earthquakes have occurred in the Changxing coal mine, leading to the deterioration of vegetation, water loss, and ecological damage.

At present, the Changxing coal mine only has 3101, 3103, 3015, and 3107 working faces that remain minable, as shown in Fig. 1. The mining area is located at the northeastern part of the mine field. Under these circumstances, the roadway backfill method in longwall mining was used to solve these

Table 1. Testing scheme.

Scheme	Aeolian sand	Loess	Cementing material
1	70	20	10
2	68	20	12
3	67	20	13
4	61	30	9
5	60	30	10
6	58	30	12
7	51	40	9
8	50	40	10
9	48	40	12

problems. In this method, backfill materials are used to fill the mined-out area, serving as a permanent stress-bearing body that supports the overburden. Overlying strata may slowly sink as a consequence; therefore it is of critical importance that the surface subsidence is effectively controlled. Additionally, by adopting this method the coal recovery can be increased from 30 to 70 %; therefore, the recoverable coal resource can reach 3 427 000 t.

3 Testing of the mechanical properties of the backfill material

3.1 Sample preparation and test scheme

Since the Changxing coal mine is located in western China, an area where the aeolian sand and loess are widespread, we used these deposits as the principal backfill materials for maximum cost reduction. To improve its resistance to deformation, the backfill material consisted of three kinds of material: aeolian sand, loess, and a cementing material. Specifically, aeolian sand and loess were used as a coarse aggregate and a fine aggregate, respectively. After mixing with the cementing material, test samples of the backfill material were prepared. The testing scheme is shown in Table 1. The mechanical properties of each backfill material were a result of triplicate tests on each sample.

3.2 Test instrument and procedure

As shown in Fig. 2, the test system mainly consists of a SANS material testing machine and a self-made compaction device. Equipped with data acquisition software, the system can obtain the mechanical parameters such as load and displacement. The compaction device comprised a steel chamber, a base, a dowel bar, and a loading plate. The internal radius, external radius, height, and wall thickness of the steel chamber were 125, 137, 305, and 12 mm, respectively. The steel chamber and base were connected by flanges. In addition, with a radius and a height of 124 and 40 mm, respectively, the loading plate is able to apply a uniform force to the samples (see Fig. 3).

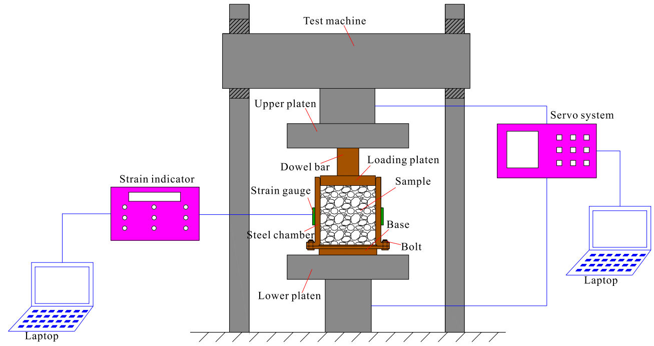

Figure 2. Schematic diagram of test system.

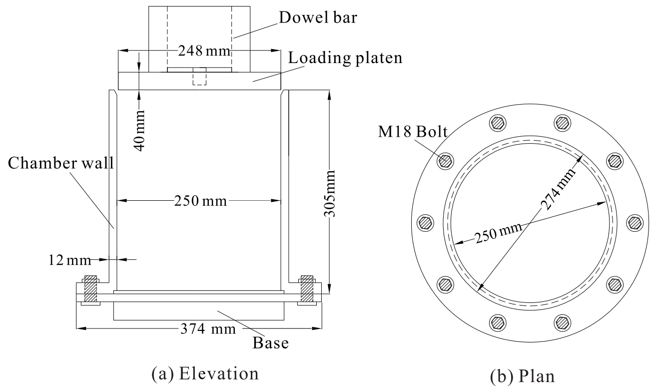

Figure 3. Plan and elevation views of the steel chamber.

The test procedure was as follows:

1. Putting the samples into the compaction device: some samples were weighed and then put into the compaction device in layers, followed by the smoothing of the sample surface.

2. Calculating the original filling height of the samples before loading: when the samples were put into the compaction device, the loading plate was put on the upper surface of the samples. The heights of the steel chamber and the dowel steel and the thickness of the loading plate were H_1 (305 mm), H_2 (100 mm), and H_3 (40 mm), respectively. Furthermore, the dowel steel exceeded the steel chamber height, which is denoted as H_4. According to the above data, the original filling height can be calculated from: $H = H_1 + H_4 - H_2 - H_3$, as shown in Fig. 4.

3. Applying axial load to the samples: before loading, the positions of the upper plate and the dowel bar of the test machine were adjusted to align the dowel bar with the center of the upper plate and let it make contact with the upper plate. Meanwhile, the displacement and load were recorded during the compaction of the samples.

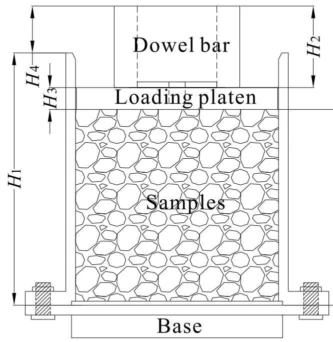

Figure 4. Original filling height of the samples before loading.

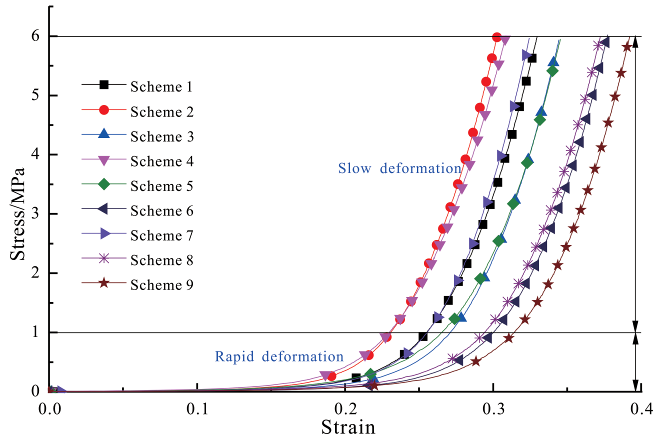

Figure 5. Stress–strain curves of backfill materials.

3.3 Analysis of test results

The stress–strain curves of the backfill materials are shown in Fig. 5, where the following features can be appreciated.

1. All the stress–strain curves had two phases:
   a. a rapid deformation phase up to 1 MPa
   b. slower deformation thereafter, up to 6 MPa.
2. During the slow deformation phase, the stress–strain relationship was quasi-linear. Obviously, Scheme 2 was the stiffest backfill material.
3. If the compaction pressure applied to the backfill material was 1 MPa or greater in the preliminary stage, the deformation of the backfill material during the later period was lower.

4 Roadway backfill technique

The principle of roadway backfill technique is shown in Fig. 6. The length of a backfilled mining roadway is usually 150 to 300 m, with a width of 5 to 10 m. The width of the unexploited coal pillars is usually 2 to 5 m. The equipment for backfilling the driving roadway includes the mining equipment and the backfill equipment. The mining equipment consists primarily of a continuous shearer, a loader, a trackless tired vehicle, etc. while the backfill equipment is primarily a material thrower, a belt conveyor, etc.

5 Strata movement characteristics resulting from different roadway driving and filling sequences

5.1 Numerical simulation method

5.1.1 Modeling and parameter selection

Based on the roadway layout, a numerical calculation model was established using FLAC$^{3\text{-}D}$ software based on working face 3101 in Changxing coal mine for roadway backfill. As shown in Fig. 7, the calculation model, with a strike length, inclination length, and height of 200, 100, and 35 m, respectively, was divided into 1 026 000 elements and 1 071 372 nodes. The bottom boundary of the model was defined by $u = v = w = 0$ (where u refers to the displacement in the x direction, v is that in the y direction, and w is that in the z direction) for full constraint. The top of the model was a free boundary, and a vertical load (1.6 MPa) is applied to simulate the overburden weight at the top of the model. The left and right boundaries were constrained by horizontal displacement. The coal and rock mass and the backfill body were simulated using a Mohr–Coulomb model and an elastic model, respectively. After a throwing force of 1 MPa was imposed on the backfill material by the material thrower, the stress–strain relationship of the backfill material had an approximate linear distribution. The elastic modulus of Scheme 2 was determined as 14 MPa. Table 2 lists the physical and mechanical parameters of the coal and rock masses.

5.1.2 Simulation scheme

The numerical simulation consisted of two schemes: single roadway driving and driving on multiple roadways. Specific details are as follows:

- Scheme 1: single roadway driving was performed on the coal seam, and the strata movement characteristics were simulated for roadway driving with excavation widths of 3, 5, 7, and 9 m, respectively. Meanwhile, the zone affected by the abutment stresses by the roadway for different widths of the driving roadway was determined.
- Scheme 2: the driving and filling sequence for multiple roadways was determined according to the zone affected by the abutment stress around the roadway. Meanwhile, the strata movement trends during driving on multiple roadways and filling were simulated for roadway widths of 3, 5, 7, and 9 m.

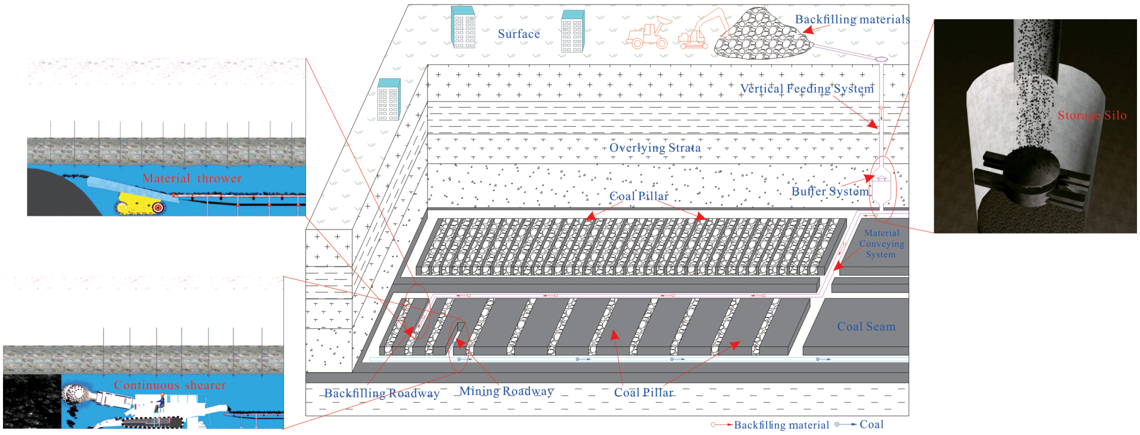

Figure 6. Principle of roadway driving with backfill technique.

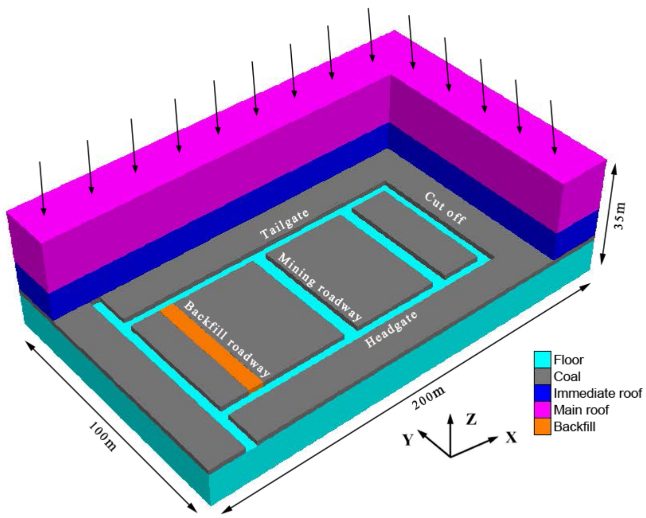

Figure 7. Numerical calculation model.

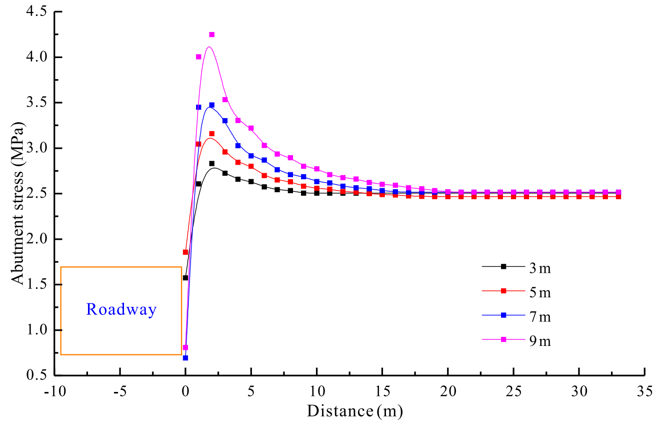

Figure 8. Distribution of abutment stresses on the roadway.

5.2 Single roadway driving

According to the simulation scheme for driving on a single roadway, the distribution of the abutment stresses by the roadway (at different widths) was obtained and is shown in Fig. 8.

As the roadway width increased, the maximum stress and the zone affected by the abutment stress on both sides of the roadway would be larger gradually. When the width of the excavation roadway ranged from 3 to 9 m, the zone affected by abutment stress was as high as 2.5 to 3.0 times the width of the excavation roadway. Therefore, the stress concentration factor is the ratio of the peak value of the abutment stress to the initial rock stress, which can be used to show the effects of the abutment stress variation with the different roadway width. If the peak value of the abutment stress changed from 2.8 to 4.3 MPa, the stress concentration factor changed from 1.1 to 1.7.

Therefore, in order to ensure the stability of the surrounding rock while driving on the roadway, the distance between two adjacent excavation roadways must be at least 3 times longer than the width of the excavated roadway.

5.3 Driving on multiple roadways

Based on the simulation of driving on a single roadway, the distance between two adjacent roadways was designed to be 3 times longer than the width of the excavation roadway during driving. Meanwhile, coal pillars with a width of 3 m were established between every second roadway. Roadway driving and filling was divided into four stages in total (see Fig. 9).

5.3.1 Strata movement trends

Based on the simulation scheme for driving on multiple roadways, the roof subsidence for different widths of roadway driving can be obtained (see Fig. 10).

Figure 10 shows the following:

Table 2. Physico-mechanical parameters of the coal and rock mass.

Rock layer	Thickness (m)	Bulk modulus (GPa)	Tensile strength (MPa)	Cohesion (MPa)	Friction angle (°)	Density ($kg\,m^{-3}$)
Main roof	11.6	1.5	2.8	1.8	32	2200
Immediate roof	4.5	0.8	1.6	0.9	28	1600
Coal seam	5.35	0.6	1.2	0.8	21	1400
Floor	7.6	1.0	1.8	0.5	28	1600

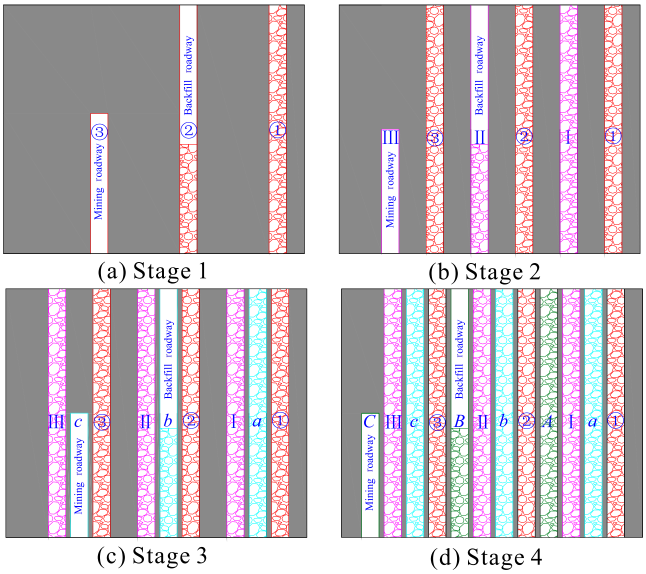

Figure 9. Simulation of driving on multiple roadways.

1. Roof subsidence gradually increased with the width of the roadway.

2. When the width of excavation roadway ranged from 3 to 9 m, the maximum roof subsidence in the first, second, third, and fourth stages varied between 3 to 14, 6 to 53, 9 to 147, and 12 to 238 mm, respectively. Additionally, roof subsidence above the coal pillar was less than that in the backfill body.

3. In the first, second, and third stages, different stresses on the coal pillar and backfill body led to a wave-shaped roof subsidence curve. In the fourth stage, the subsidence curve tended to be smooth after the roof was stabilized.

In summary, the design of a roadway driving sequence and the roadway length can reduce the effects of mining between two roadways. Meanwhile, the joint support of coal pillars and the backfill body can effectively control strata movement.

5.3.2 Stress distribution in the mining field

Figure 11 shows the stress distribution in the mining field for different roadway widths during driving on multiple roadways. At the same stage, the stress in the mining field gradually increased with the increasing of roadway width. Meanwhile, for roadways of the same width, driving and filling at each stage gradually increased the stress in the mining field. When the width of the roadway changed from 3 to 9 m, the maximum stresses in the first, second, third, and fourth stages in the mining field were between 2.8 to 3.9, 3.1 to 4.9, 3.6 to 6.6, and 4.3 to 7.4 MPa, respectively. As the overlying strata subsided with driving and filling at each stage, the coal pillars were gradually compressed, and the stress by the coal pillars increased, reaching a maximum in the middle of the mining field. The backfill materials as the main supporting body effectively changed the stress state in the surrounding rock during the backfill process of the driving roadway. Meanwhile, the design of the roadway driving sequence and the roadway length avoided the superposition of mine-induced stress and dissipated the effects of the mining.

5.3.3 Safety evaluation of coal pillars

The stability of the established coal pillars must be evaluated for roadway backfill method during mining. The safety coefficient is most appropriate for consideration when designing underground coal pillars – the larger the safety coefficient is, the lower the failure probability of the coal pillars. The safety coefficient of a coal pillar (F) is the ratio of the compressive strength (σ_c) of the coal pillar to the average compressive stress (σ_p) by the entire coal pillar (Peng, 2008):

$$F = \frac{\sigma_c}{\sigma_p}. \quad (1)$$

According to our experience in the Changxing coal mine, when the width of the established coal pillars was 3 m, the safety the coefficient of the coal pillars must be 2 if the coal pillar was not to fail. The compressive strength of the coal was 23.1 MPa. According to the stress distribution in the mining field during driving on multiple roadways, the stress by a coal pillar peaked when the width of the driving roadway was 9 m. Therefore, coal pillar stability was evaluated at an excavation roadway width of 9 m. At a roadway width of 9 m, the maximum stress by a coal pillar was 7.4 MPa,

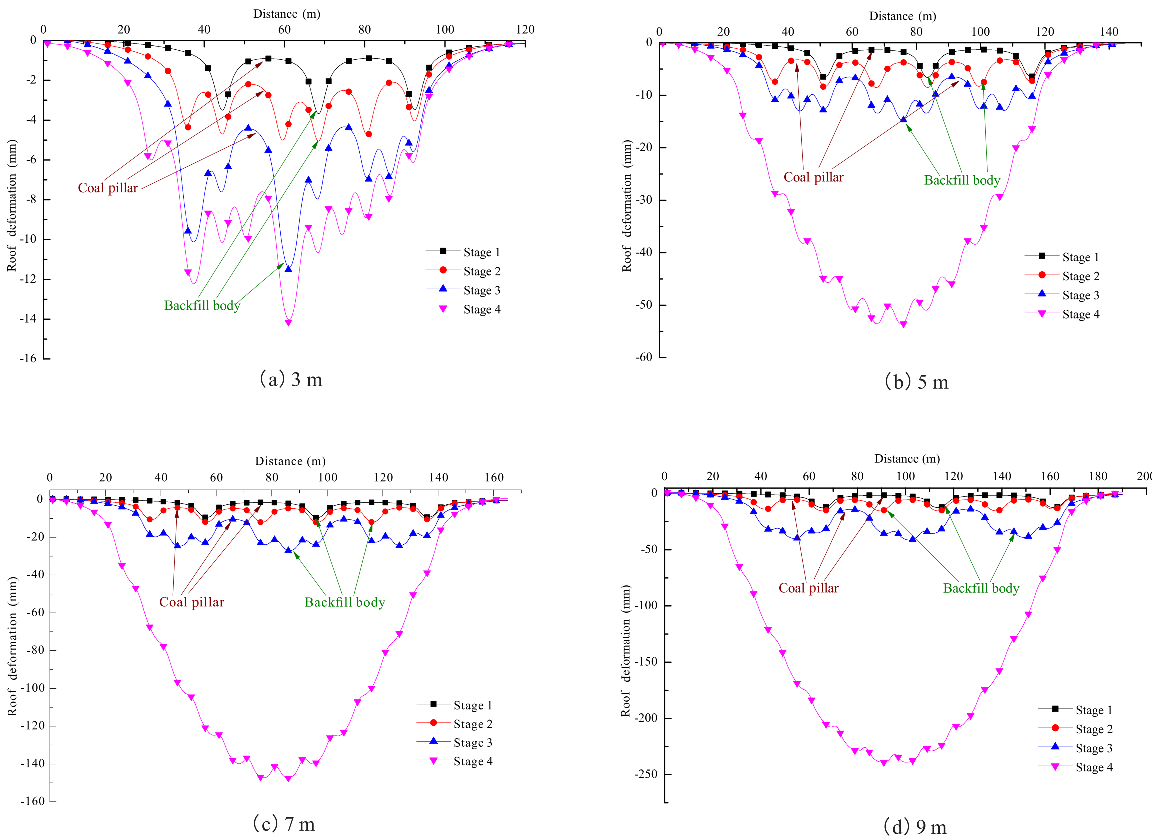

Figure 10. Roof subsidence with different width of roadway.

and the safety coefficient of the coal pillar was 3.12. When the safety coefficient of the coal pillars was greater than 2.5, the failure probability of the coal pillars was approximately equal to 0 % (Peng, 2008), so the coal pillars did not become unstable.

The development of the plastic zone in the mining field when the width of excavation roadway was 9 m is shown in Fig. 12.

As shown in Fig. 12, plastic zones with thicknesses of about 0.5 m were generated on both sides of the coal pillars, which were supported by the backfill materials. The width of the elastic zones that developed was 2 m, accounting for 67 % of the coal pillar cross section, which demonstrated that no instability was generated therein.

6 Movement characteristics of strata after quadratic stabilization when backfilling the driving roadway during mining

When backfilling mining is used to mine a coal seam, the overlying strata are disturbed, inducing secondary settlement. The first strata movement occurred when the original reservoir was formed, which is called "first stabilization". The second was primarily caused by the gradual compression of the overlying strata on the backfill bodies and the coal pillars. During this process, the compressed backfill bodies and coal pillars give rise to the movement of the overlying strata, finally stabilizing it, which is called "quadratic stabilization". The movement of the strata after quadratic stabilization during backfill mining of a driving roadway is a dynamic process. It includes the mining of coal seams and backfilling the driving roadway during the mining, the compression of the backfill bodies and coal pillars, the gradual subsidence of the overlying strata, and the final stabilization of the overlying strata. The roof subsidence profiles after quadratic stabilization of the backfilled driving roadway during mining are shown for different excavation roadway widths in Fig. 13.

The results in Fig. 13 allow the following conclusions to be drawn:

1. The roof subsidence increased with an increase in the excavation roadway width after quadratic stabilization. When the width of the excavation roadway changed from 3 to 9 m, the maximum roof subsidence changed from 12 to 238 mm.

2. The backfill body as the supporting body absorbed and transferred the mining-induced stress. With a continuous compressing force from the overlying strata, the

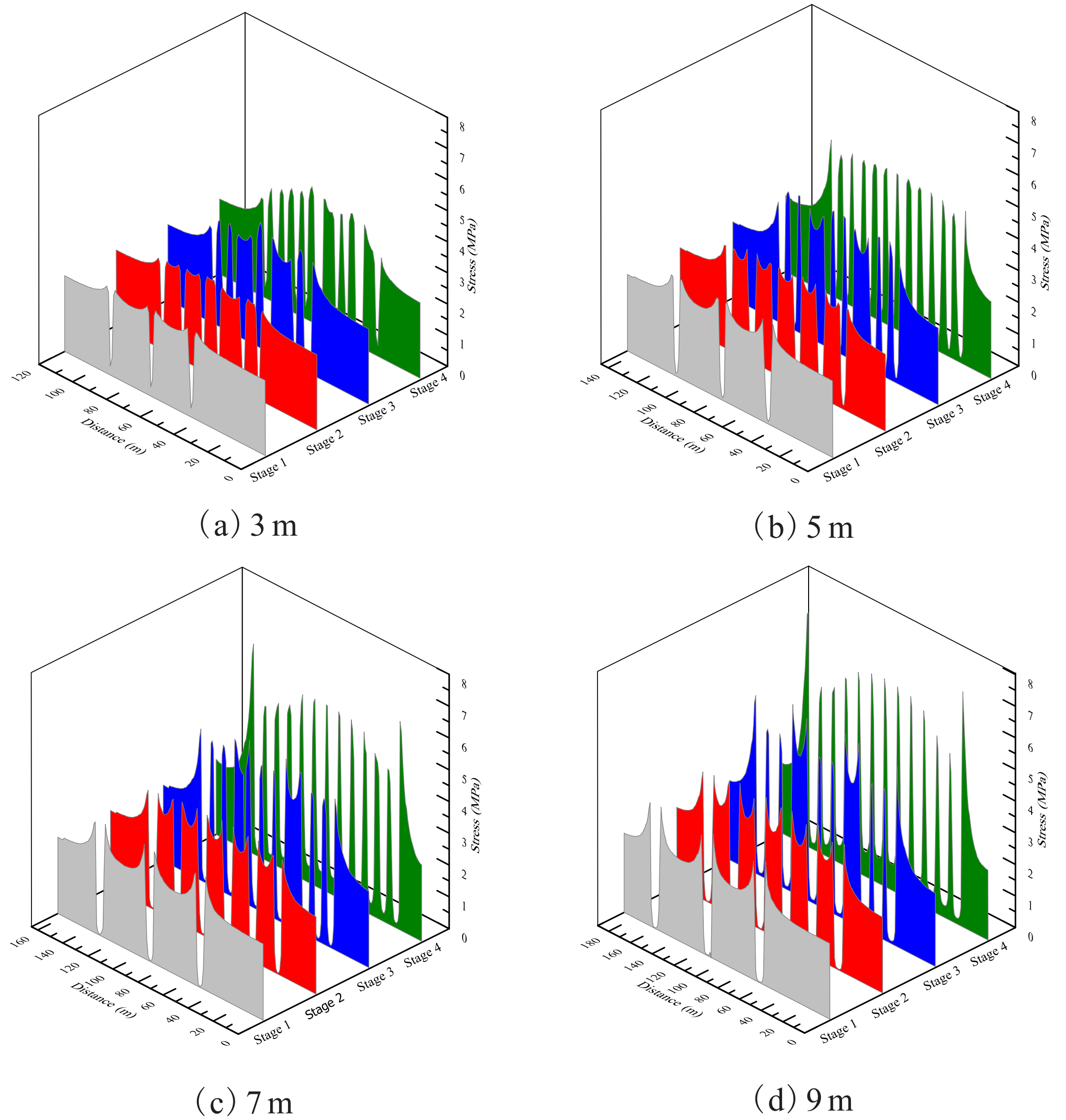

Figure 11. Stress distributions with different width of roadway.

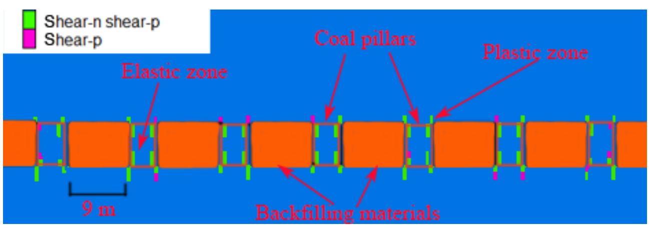

Figure 12. Plastic zone distribution for a 9 m wide excavation roadway.

porosity of backfill body gradually decreased, leading to better control of the stability of the overlying strata.

7 Analysis of an engineering application

7.1 Layout of the mining system

Considering the width of the road header and the control of the rock surrounding the roadway, the excavation roadway at the working face was designed to be 7 m wide, with 3 m wide coal pillars. Figure 14 shows the working face layout used in the Changxing coal mine.

7.2 Optimization of the driving and filling sequence

According to the distribution of the abutment stress by the roadway in single roadway driving, when the width of the excavation roadway was 7 m, the zone affected by the abutment stress imposed on the roadway was 18 m wide (see Fig. 8).

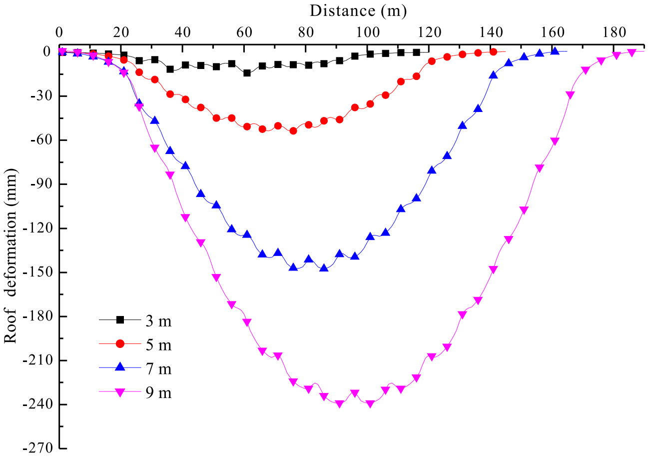

Figure 13. Roof subsidence after quadratic stabilization.

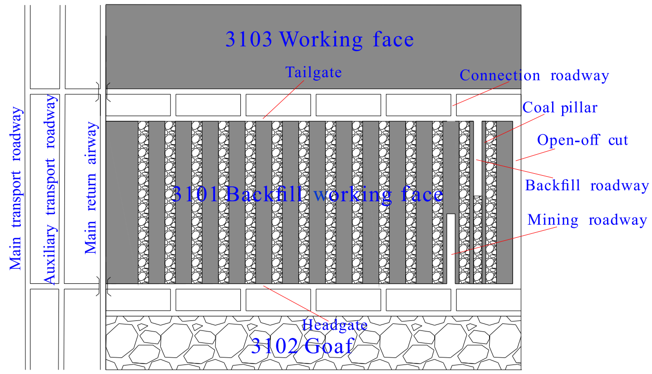

Figure 14. Layout of the mining system used in the Changxing coal mine.

After accounting for the safety factors, we determined that the distance between two adjacent driving roadways should be 21 m, which was beyond the scope of stress influence. In the simulation scheme for driving on multiple roadways, when the width of excavation roadway was 7 m, the maximum roof subsidence in the first, second, third, and fourth stages were 9, 12, 26, and 238 mm, respectively. Moreover, the maximum stresses in the first, second, third, and fourth stages in the mining field were 3.6, 3.9, 4.9, and 6.6 MPa, respectively. According to the safety coefficient calculation of a coal pillar (Eq. 1), the safety coefficient of the coal pillar was 3.5 at a roadway width of 7 m, which meant the failure probability of the coal pillars was approximately equal to 0 %.

Thus, in order to avoid the stress influence and improve the coal recovery ratio, the coal seam must be excavated and filled in stages which could make two adjacent driving roadways beyond the scope of stress influence. The design of the roadway driving and filling sequence in the 3101 working face of the Changxing coal mine can be divided into four stages.

1. In stage 1, by driving from the headgate to the tailgate at the working face, roadway (2) was produced. Afterwards, roadway (1) was excavated while roadway (1) was filled. As shown in Fig. 15a, this process continued until the all of the driving and filling in stage 1 were finished.

2. In stage 2, the coal pillar was mined, resulting in the formation of roadway I. Meanwhile, coal pillars with a width of 3 m were established on both sides of roadway I. Afterwards, as shown in Fig. 15b, driving on roadway I proceeded while roadway I was filled. This process continued until the driving and filling in stage 2 was finished.

3. In stage 3, the coal pillar on the right-hand side of roadway I was mined, resulting in the formation of roadway a. Meanwhile, 3 m wide coal pillars were established on both sides of roadway a. Afterwards, as shown in Fig. 15c, driving on roadway b proceeded while roadway a was filled. This process continued until the driving and filling in stage 3 was finished.

4. In stage 4, the coal pillar on the left-hand side of roadway I was mined, resulting in the formation of roadway A. Meanwhile, 3 m wide coal pillars were established on both sides of roadway A. Afterwards, as shown in Fig. 15d, driving on roadway B proceeded while roadway A was filled. This process continued until the driving and filling in stage 4 was finished, as shown in Fig. 15e.

7.3 Application effect analysis

At present, the 3101 working face has been advanced for 170 m. To thoroughly study rock strata movement and deformation rules in the Changxing coal mine, ground movement observation stations were built in corresponding position above the working face. Surface movement observing proceeded from 5 January to 5 December 2014, and the curve of surface subsidence measurements against time can be seen in Fig. 16.

According to the analysis of the surface monitoring data, the accumulated maximum subsidence at the surface monitoring point is 15 mm and the maximum horizontal deformation is 0.8 mm m^{-1}. These are both controlled within Grade I deformation specified by State Bureau of Coal Industry. The analysis indicated that the ground basically had no obvious deformation after the implementation of the roadway backfill method at 3101 working face.

When the roadway backfill method was adopted in the Changxing coal mine, the coal recovery ratio approached 70 % and the compression ratio was more than 90 %. Also, the loess and aeolian sand treatment capacity reached

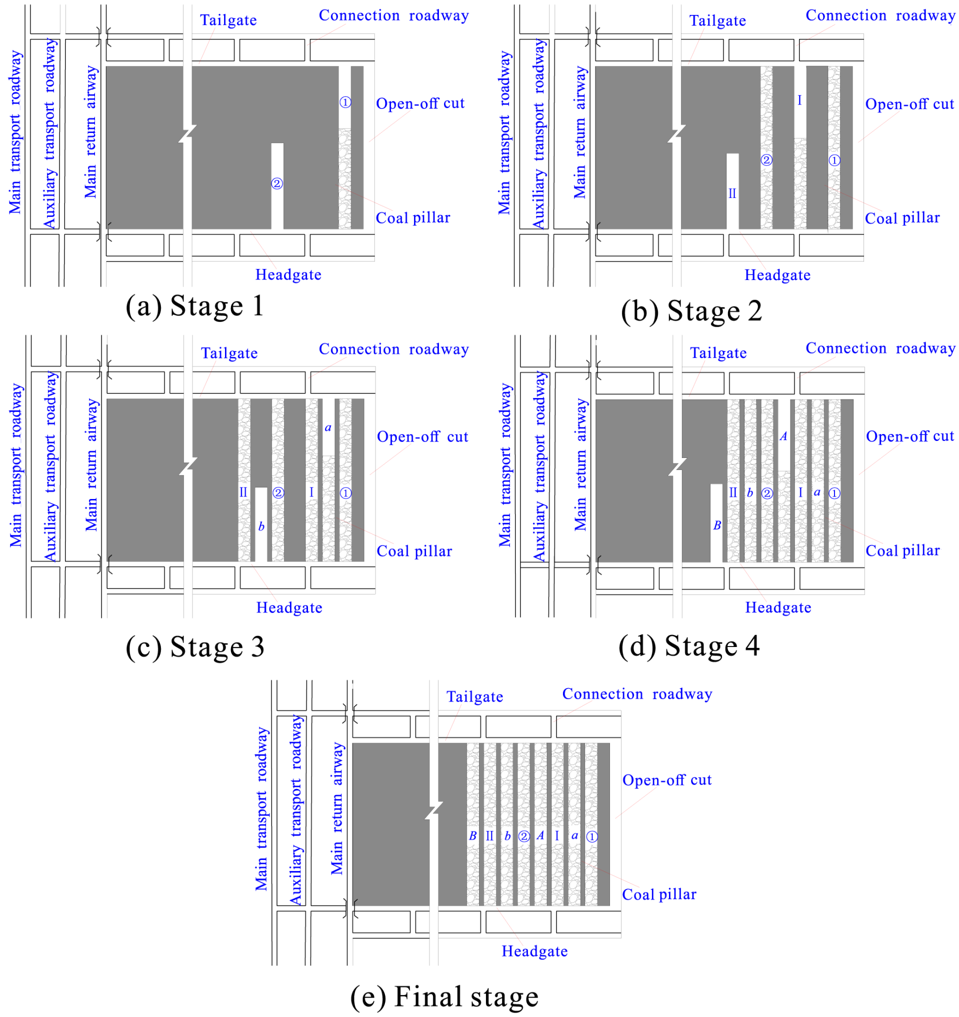

Figure 15. Design of the driving and filling sequence in the backfill of the driving roadway during mining.

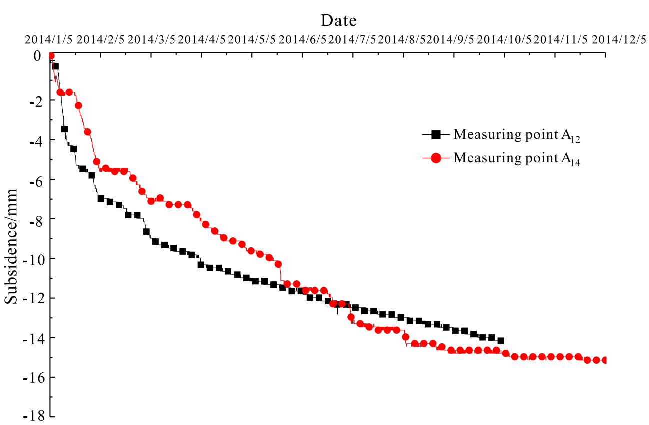

Figure 16. Curves of surface subsidence measurements against time.

718 000 t a^{-1}, with a large amount of solid mine wastes being used as backfill materials for filling goaf. The overlying strata of the goaf is well supported to prevent strata movement and surface subsidence, thereby protecting ecological environment at the local mining area. Successful application of roadway backfill method in the Changxing coal mine may provide some references to other coal mines in the western area for improving coal recovery while protecting the environment.

8 Conclusions

By studying the strata movement characteristics when backfilling the driving roadway during mining, we arrived at the following conclusions:

1. The mining rate of the room and pillar method is less than 40 %. Meanwhile, the coal pillars creep over time and gradually fail. During pillar failure, the roof

strata become fractured and their collapse progresses upwards. The method of backfilling the driving roadway during longwall mining was proposed to solve these problems. In this method, the mined out area is backfilled to serve as a permanent stress-bearing body that supports the overburden. The overlying strata may slowly sink as a consequence, and therefore it is of critical importance that strata movement and surface subsidence are effectively controlled.

2. Aeolian sand, loess, and cementing materials were used to prepare the backfill materials in this study. Testing determined the mechanical properties and compositions of the backfill materials.

3. The strata movement characteristics when driving on a single roadway were obtained, and the zone affected by abutment stress in the mining field was determined by simulation and used to optimize the sequence of driving on multiple roadways accompanied by the acquisition of the strata movement characteristics when driving on multiple roadways.

4. Roadway backfill technique during longwall mining of the 3101 working face of the Changxing coal mine was used as an engineering case study in this work. Based on the strata movement characteristics of driving on single and multiple roadways, the driving and filling sequence of the 3101 working face was optimized to avoid the added effects of mining-induced stresses.

5. According to the analysis of the surface monitoring data, the accumulated maximum subsidence is 15 mm and the maximum horizontal deformation is $0.8\,\mathrm{mm\,m^{-1}}$, which indicated that the ground basically had no obvious deformation after the implementation of the roadway backfill method at 3101 working face. Also the coal recovery ratio approached 70 % and the compression ratio was more than 90 %.

9 Data availability

The underlying research data are available upon request from the corresponding author.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This research was supported by the Qing Lan project (Education Department of Jiangsu, 2014(23)), Foundation for Distinguished professor of Jiangsu Province (Education Department of Jiangsu, 2015(29)), and National Natural Science Foundation of China (51504238).

Edited by: M. Parise
Reviewed by: two anonymous referees

References

An, B. F., Miao, X. X., Zhang, J. X., Ju, F., and Zhou, N.: Overlying strata movement of recovering standing pillars with solid backfilling by physical simulation, Int. J. Min. Sci. Tech., 26, 301–307, doi:10.1016/j.ijmst.2015.12.017, 2016.

Bell, F. G. and Bruyn, I. A.: Subsidence problems due to abandoned pillar workings in coal seams, B. Eng. Geol. Environ., 57, 225–237, doi:10.1007/s100640050040, 1999.

Castellanza, R., Gerolymatou, E., and Nova, R.: Evaluation and remediation of an abandoned gypsum mine, Rock Mech. Rock Eng., 41, 377–401, doi:10.1007/s00603-007-0142-y, 2008.

Castellanza, R., Nova, R., and Orlandi, G.: Flooded gypsum mine remedial by chamber filling, J. Geotech. Geoenviron. Eng., 136, 629–639, doi:10.1061/(ASCE)GT.1943-5606.0000249, 2010.

Chen, S. J., Guo, W. J., Zhou, H., and Wen, G. H.: Structure model and movement law of overburden during strip pillar mining backfill with cream-body, J. China Coal Soc., 36, 1081–1086, 2011.

Chen, S. J., Zhou, H., Guo, W. J., Wang, H. L., and Sun, X. Z.: Study on long-term stress and deformation characteristics of strip pillar, J. Min. Safety. Eng., 29, 376–380, 2012.

Cui, X. M., Gao, Y. G., and Yuan, D. B.: Sudden surface collapse disasters caused by shallow partial mining in Datong coalfield, China, Nat. Hazards, 74, 911–929, doi:10.1007/s11069-014-1221-5, 2014.

Ding, H. D., Miao, X. X., Ju, F., Wang, X. L., and Wang, Q. C.: Strata behavior investigation for high-intensity mining in the water-rich coal seam, Int. J. Min. Sci. Tech., 24, 299–304, doi:10.1016/j.ijmst.2014.03.002, 2014.

Ghasemi, E., Ataei, M., Shahriar, K., Sereshki, F., Jalali S. E., and Ramazanzadeh, A.: Assessment of roof fall risk during retreat mining in room and pillar coal mines, Int. J. Rock Mech. Min., 54, 80–89, doi:10.1016/j.ijrmms.2012.05.025, 2012.

Guo, L. Q., Cai, Q. P., and Peng, X. Q.: Effect of strength criterion on design of strip coal pillar, Rock Soil Mech., 35, 777–782, 2014a.

Guo, G. L., Zhu, X. J., Zha, J. F., and Wang, Q.: Subsidence prediction method based on equivalent mining height theory for solid backfilling mining, T. Nonferr. Metal. Soc. China, 24, 3302–3308, doi:10.1016/S1003-6326(14)63470-1, 2014b.

Gutierrez, F., Parise, M., De Waele, J., and Jourde, H.: A review on natural and human-induced geohazards and impacts in karst, Earth Sci. Rev., 138, 61–88, doi:10.1016/j.earscirev.2014.08.002, 2014.

Jiang, B. Y., Wang, L. G., Lu, Y. L., Sun, X. K., and Jin, G.: Ground pressure and overlying strata structure for a repeated mining face of residual coal after room and pillar mining, Int. J. Min. Sci. Tech., 26, 571–575, doi:10.1016/j.ijmst.2016.05.017, 2016.

Junker, M. and Witthaus, H.: Progress in the research and application of coal mining with stowing, Int. J. Min. Sci. Tech., 23, 7–12, doi:10.1016/j.ijmst.2013.01.002, 2013.

Lollino, P., Martimucci, V., and Parise, M.: Geological survey and numerical modeling of the potential failure mechanisms of underground caves, J. Geosys. Eng., 16, 100–112, doi:10.1080/12269328.2013.780721, 2013.

Parise, M.: Rock failures in karst, in: Landslides and Engineered Slopes, in: Proc. 10th International Symposium on Landslides, edited by: Cheng, Z., Zhang, J., Li, Z., Wu, F., and Ho K., Xi'an (China), 30 June–4 July 2008, 1, 275–280, 2008.

Parise, M.: A present risk from past activities: sinkhole occurrence above underground quarries, Carbonate. Evaporite., 27, 109–118, doi:10.1007/s13146-012-0088-3, 2012.

Parise, M.: Karst geo-hazards: causal factors and management issues, Acta Carsologica, 44, 401–414, doi:10.3986/ac.v44i3.1891, 2015.

Parise, M. and Lollino, P.: A preliminary analysis of failure mechanisms in karst and man-made underground caves in Southern Italy, Geomorphology, 134, 132–143, doi:10.1016/j.geomorph.2011.06.008, 2011.

Parise, M., Closson, D., Gutierrez, F., and Stevanovic, Z.: Anticipating and managing engineering problems in the complex karst environment, Environ. Earth Sci., 74, 7823–7835, doi:10.1007/s12665-015-4647-5, 2015.

Pasten, D., Estay, R., Comte, D., and Vallejos, J.: Multifractal analysis in mining microseismicity and its application to seismic hazard in mine, Int. J. Rock Mech. Min. Sci., 78, 74–78, doi:10.1016/j.ijrmms.2015.04.020, 2015.

Peng, S. S.: Coal mine ground control, 3rd edn., edited by: Syd, S., Peng Publisher, Morgantown, WV, USA, 198–210, 2008.

Shi, L. Q. and Singh, R. N.: Study of mine water inrush from floor strata through faults, Mine Water Environ., 20, 140–147, doi:10.1007/s10230-001-8095-y, 2001.

Si, H., Bi, H. P., Li, X. H., and Yang, C. H.: Environmental evaluation for sustainable development of coal mining in Qijiang, Western China, J. Coal Geol., 81, 163–168, doi:10.1016/j.coal.2009.11.004, 2010.

Sun, X. K. and Wang, W.: Theoretical research on high water material replacement mining the strip coal pillar above confined aquifer, J. China Coal Soc., 36, 909–913, 2011.

White, W. B.: Karst hydrology: recent developments and open questions, Eng. Geol., 65, 85–105, doi:10.1016/S0013-7952(01)00116-8, 2002.

Vigna, B., Fiorucci, A., Banzato, C., Forti, P., and De Waele, J.: Hypogene gypsum karst and sinkhole formation at Moncalvo (Asti, Italy), Z. Geomorphologie, 54, 285–306, doi:10.1127/0372-8854/2010/0054S2-0015, 2010.

Yu, W. J. and Wang, W. J.: Strata movement induced by coal-pillar under three circumstances exchanged by gangue backfill and quadratic stability law, Chinese J. Rock Mech. Eng., 30, 105–112, 2011.

Zhai, C., Xiang, X. W., Xu, J. Z., and Wu, S. L.: The characteristics and main influencing factors affecting coal and gas outbursts in Chinese Pingdingshan mining region, Nat. Hazards, 82, 507–530, doi:10.1007/s11069-016-2195-2, 2016.

Zhang, J. X., Miao, X. X., Mao, X. B., and Chen, Z. W.: Research on waste substitution extraction of strip extraction coal-pillar mining, Chinese J. Rock Mech. Eng., 26, 2687–2693, 2007.

Zhang, J. X., Zhou, N., Huang, Y. L., and Zhang, Q.: Impact law of the bulk ratio of backfilling body to overlying strata movement in fully mechanized backfilling mining, J. Min. Sci., 47, 73–84, doi:10.1134/S1062739147010096, 2011.