1 Roadway backfill method to prevent geo-hazards induced by room
2 and pillar mining: a case study in Changxing coal mine, China

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

19 1 Introduction

20 Recently, due to the high intensity and large scale of coal mining around the world, problems associated with resources and
21 the environment have become more severe with each passing day, and many mining induced hazards have been caused (Shi
22 and Singh 2001; Castellanza et al. 2010; Pasten et al. 2015; Zhai et al. 2016). The effects of these problems are especially
23 prominent in the ecologically vulnerable areas of western China (Si et al. 2010; Ding et al. 2014). Many small and medium-
24 sized coal mines in this area use room and pillar mining method (Kostecki and Spearing 2015), and have a mining rate of
25 less than 30%, which leading to abandonment of the coal resources in underground. In addition, the burial depth of the coal
26 seams in the region is usually shallower. During mining, geological behaviour becomes more important, threatening mine
27 production safety and usually causing unpredictable disasters, such as surface subsidence, landslides and water inrush caused
28 by karst environments (White 2002; Parise 2012; Lollino et al. 2013; Parise 2015). In particular, when karst caves are at
29 shallow depth, the effects at the ground surface may be extremely severe (Parise and Lollino 2011), and the direct

30 connection between the surface and the underlying karst aquifers usually function as a channel for water inrush (Gutierez et
31 al. 2014), thus posing a great threat to coal mines. At present, previous studies proposed strip mining (Chen et al. 2012; Guo
32 et al. 2014a) to resolve these problems. However, strip mining resulted in a low mining rate of coal resources as well as other
33 problems. To resolve these difficulties, this research proposes roadway backfill technique in longwall mining based on the
34 solid backfill mining method (Zhang et al. 2011; Junker and Witthaus 2013; Guo et al. 2014b). This method has been
35 recently developed and has become popular and applied on a large scale, providing an effective solution to the previously
36 mentioned problems.

37   Recently, research into the strip filling method has promoted the development of the roadway filling method and its
38 underlying theory (Zhang et al. 2007; Yu and Wang 2011; Chen et al. 2011; Sun and Wang 2011), but few studies have been
39 conducted on backfilling the driving roadway during longwall mining, especially from the perspective of the strata
40 movement characteristics. Moreover, different types of backfill materials with different mechanical properties exist, and if
41 the room and pillar mining method is adopted, strata behaviour becomes the most important factor at shallow burial depths.
42 Consequently, the characteristics of the strata movement in regions mined using this approach are significantly different
43 from those in traditionally-mined regions. The room and pillar mining method is normally used for shallow mines in western
44 China to prevent the overlying strata from caving in and collapsing. A great quantity of coal resources is abandoned
45 underground due to the use of the room and pillar method, which has caused a huge waste of coal resources. Additionally,
46 the coal pillars creep over time and gradually fail (Bell and Bruyn 1999; Castellanza et al. 2008). During pillar failure, the
47 roof strata become fractured and the collapse progresses upwards (Ghasemi et al. 2012; Cui et al. 2014). Finally, surface
48 subsidence results in building damage, environmental destruction, etc. The Changxing coal mine is used as a case study in
49 this paper, and the roadway backfill method is proposed to solve the problems discussed above. We tested the mechanical
50 properties of a backfill material composed of common aeolian sand, loess, and a cementing material. We also simulated
51 strata movement characteristics with different roadway driving and filling sequences by FLAC^{3D} software. Finally, we used
52 the research results to design the 3101 working face in the Changxing coal mine.

2 Geological and mining conditions

54 The room and pillar mining method was originally adopted in the Changxing coal mine, resulting in a mining rate of only
55 30%. In addition, problems such as severe surface subsidence and significant coal loss caused by the instability of the mined
56 rooms and coal pillars have threatened the mining field, as shown in Fig. 1. Meanwhile, due to coal pillar failure, magnitude
57 2.5 and 2.8 earthquakes have occurred in the Changxing coal mine, leading to the deterioration of vegetation, water loss and
58 ecological damage. At present, only the integrated coal areas in the 3101, 3103, 3015, and 3107 working faces can be mined
59 in Changxing coal mine. Under these circumstances, roadway backfill method in longwall mining was used to solve these
60 problems. In this method, backfill materials are used to fill the mined-out area, serving as a permanent stress bearing body
61 that supports the overburden. Overlying strata may slowly sink as a consequence, therefore it is of critical importance that

62 strata movement and surface subsidence is effectively controlled. Additionally, the mining rate could be improved to a great

63 degree. The primary mineable coal bed of the mining field was designed as a coal seam with an average thickness, angle, and

64 burial depth of 5.35 m, 0.5 °, and approximately 130 m, respectively. The immediate roof, main roof, and floor are siltstone,

65 fine-sandstone, and carbonaceous mudstone with average thicknesses of 4.5 m, 11.6 m, and 7.6 m, respectively.

66 3 Testing of the mechanical properties of the backfill material

67 3.1 Sample preparation & test scheme

68 The Changxing coal mine is located in western China, where the surface of the earth is covered by aeolian sand and loess, so

69 we used aeolian sand and loess as the principal backfill materials for maximum cost reduction. To improve its resistance to

70 deformation, the backfill material was comprised of three kinds of material: aeolian sand, loess, and a cementing material.

71 Specifically, aeolian sand and loess were used as a coarse aggregate and a fine aggregate, respectively. After mixing with the

72 cementing material, test samples of the backfill material were prepared. The testing scheme is shown in Table 1. The

73 mechanical properties of each backfill material were a result of triplicate tests on each sample.

74 3.2 Test instrument

75 The SANS material testing machine was used and provided a maximum axial force of 300 kN over a cross-head

76 displacement range of 250 mm. The compaction device was a home-made compaction steel chamber containing the backfill

77 material. Its inner diameter was 125 mm and its outer diameter was 137 mm, while its height was 305 mm. The radius and

78 height of the compression piston were 124 mm and 40 mm, respectively (Li et al. 2014). A load was applied by the test

79 machine via a compression piston fitted to the compaction device (see Fig. 2).

80 3.3 Analysis of test results

81 The stress-strain curves of the backfill materials are shown in Fig. 3.

82 Fig. 3 shows that: (1) The stress-strain curves all had two phases: a) a rapid deformation phase up to 1 MPa, and b)

83 slower deformation thereafter, up to 6 MPa; (2) During the slow deformation phase, the stress-strain relationship was quasi-

84 linear. Obviously, Scheme 2 was the stiffest backfill material; (3) If the compaction pressure applied to the backfill material

85 was 1 MPa or greater in the preliminary stage, the deformation of the backfill material during the later period was less.

86 4 Roadway backfill technique

87 The principle of roadway backfill technique is shown in Fig. 4. The length of a backfilled mining roadway is usually 150 to

88 300 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

89 the driving roadway includes the mining equipment and the backfill equipment. The mining equipment consists primarily of

90 a continuous shearer, a loader, a trackless tired vehicle, etc. while the backfill equipment is primarily a material thrower, a

91 belt conveyor, etc.

92   The design of the technique for roadway backfill includes the mining process and the backfill process. The mining

93 process is implemented by the continuous shearer, the loader and the trackless tyred vehicle, retreating from the headgate to

94 the tailgate, whereas the backfill material is filled backwards from the headgate to the tailgate in the backfill process. The

95 backfill materials are conveyed to an underground storage silo by a vertical feeding system, then transported to the backfill

96 roadway, and thrown at high speed into the backfill roadway by the material thrower.

97 5 Strata movement characteristics resulting from different roadway driving and filling sequences

98 5.1 Numerical simulation method

99 5.1.1 Modelling and parameter selection

100 Based on the roadway layout (Fig. 4), a numerical calculation model was established using FLAC^{3D} software based on

101 working face 1301 in Changxing coal mine for roadway backfill. As shown in Fig. 5, the calculation model, with a strike

102 length, inclination length, and height of 200 m, 100 m, and 35 m, respectively, was divided into 1,026,000 elements and

103 1,071,372 nodes. A uniform stress of 1.6 MPa was applied on the upper boundary with a level constraint and a vertical

104 restraint imposed on the surrounding boundaries and bottom boundary respectively. The coal and rock mass and the backfill

105 body were simulated using a Mohr-Coulomb model and an elastic model, respectively. After a throwing force of 1 MPa was

106 imposed on the backfill material by the material thrower, the stress-strain relationship of the backfill material had an

107 approximate linear distribution. The elastic modulus of Scheme 2 was determined as 14 MPa. Table 2 lists the physical and

108 mechanical parameters of the coal and rock masses.

109 5.1.2 Simulation scheme

110 The numerical simulation consisted of two schemes: single roadway driving and driving on multiple roadways. Specific

111 details are as follows:

112   Scheme 1: Single roadway driving was performed on the coal seam, and the strata movement characteristics were

113 simulated for roadway driving with excavation widths of 3 m, 5 m, 7 m, and 9 m respectively. Meanwhile, the zone affected

114 by the abutment stresses borne by the roadway for different widths of the driving roadway was determined.

115   Scheme 2: The driving and filling sequence for multiple-roadways was determined according to the zone affected by

116 the abutment stress around the roadway. Meanwhile, the strata movement trends during driving on multiple roadways and

117 filling were simulated for roadway widths of 3 m, 5 m, 7 m, and 9 m.

5.2 Single roadway driving

According to the simulation scheme for driving on a single roadway, the distribution of the abutment stresses borne by the roadway (at different widths) was obtained and is shown in Fig. 6.

As shown in Fig. 6, increasing the roadway width increased the maximum stress and the zone affected by the abutment stress on both sides of the roadway. When the width of the excavation roadway ranged from 3 m 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. 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.

Finally, 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. 7).

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 (Fig. 8).

Fig. 8 shows that: (1) Roof subsidence gradually increased with the width of the roadway. On roadways of the same width, driving and filling at each stage increased the roof subsidence; (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 4 to 14 mm, 5 to 16 mm, 9 to 43 mm, and 16 to 252 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 stabilised.

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 established coal pillars and the backfill body can effectively control strata movement.

5.3.2 Stress distribution in the mining field

Fig. 9 shows the stress distribution in the mining field for different roadway widths during driving on multiple roadways.

The following conclusions were drawn from the results shown in Fig. 9: (1) At the same stage, the stress on the mining field gradually increased with increasing roadway width. Meanwhile, for roadways of the same width, driving and filling at

148   each stage gradually increased the stress in the mining field; (2) When the width of the roadway changed from 3 to 9 m, the

149   maximum stresses in the first, second, third, and fourth stages in the mining field were between 2.8 to 3.9 MPa, 3.1 to 4.3

150   MPa, 3.8 to 5.9 MPa, and 4.3 to 7.4 MPa, respectively; (3) The overlying strata subsided with driving and filling at each

151   stage. As a result, the coal pillars were gradually compressed, and the stress borne by the coal pillars increased, reaching a

152   maximum in the middle of the mining field; (4) As the main supporting body, the backfill effectively changed the stress state

153   in the surrounding rock during the backfill process of the driving roadway. Meanwhile, the design of the roadway driving

154   sequence and the roadway length avoided the superposition of mine-induced stress bulbs, and dissipated the effects of the

155   mining.

5.3.3 Safety evaluation of coal pillars

157   The stability of the established coal pillars must be evaluated for roadway backfill method during mining. The safety

158   coefficient is most appropriate for consideration when designing underground coal pillars - the larger the safety coefficient,

159   the lower the failure probability of the coal pillars. The safety coefficient of a coal pillar (k) is the ratio of the average

160   compressive stress (σ_p) borne by the entire coal pillar to the compressive strength (σ_c) of the coal pillar (Peng 2008):

161    $k = \frac{\sigma_p}{\sigma_c}$,   (1)

162   According to our experience in the Changxing coal mine, when the width of the established coal pillars was 3 m, the

163   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

164   23.1 MPa. According to the stress distribution in the mining field during driving on multiple roadways, the stress borne by a

165   coal pillar peaked when the width of the driving roadway was 9 m. Therefore, coal pillar stability was evaluated at an

166   excavation roadway width of 9 m, as shown in Fig. 8(d). At a roadway width of 9 m, the maximum stress borne by a coal

167   pillar was 7.4 MPa, and the safety coefficient of the coal pillar was 3.12. When the safety coefficient of the coal pillars was

168   greater than 2.5, the failure probability of the coal pillars was approximately equal to 0% (Peng 2008), so the coal pillars did

169   not become unstable.

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

171   10.

172   As shown in Fig. 10, plastic zones with thicknesses of 0.5 m were generated on both sides of the coal pillars, which

173   were supported by the backfill materials. The width of the elastic regions that developed was 2 m, accounting for 67% of the

174   coal pillar cross-section, which demonstrated that no instability was generated therein.

6 Movement characteristics of strata after quadratic stabilisation 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. 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 stabilising it. The movement of the strata after quadratic stabilisation 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 stabilisation of the overlying strata. The roof subsidence profiles after quadratic stabilisation of the backfilled driving roadway during mining are shown for different excavation roadway widths in Fig. 11.

The results in Fig. 11 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 16 to 252 mm; (2) As the supporting body, the backfill body absorbed and transferred the mining-induced stress. With a continuous compressing force from the overlying strata, the 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. Fig. 12 shows the layout used in the Changxing coal mine.

7.2 Optimisation of the driving and filling sequence

According to the distribution of the abutment stress borne 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. After accounting for the safety factors, we determined that the distance between two adjacent driving roadways should be 21 m.

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:

Driving and filling in stage 1: by driving from the head gate to the tailgate at the working face, roadway ① was produced. Afterwards, roadway ② was excavated while roadway ① was filled. As shown in Fig. 13(a), this process continued until the all of the driving and filling in stage 1 were finished.

205   Driving and filling in stage 2: the coal pillar was mined, resulting in the formation of roadway Ⅰ. Meanwhile, coal

206 pillars with a width of 3 m were established on both sides of roadway Ⅰ. Afterwards, as shown in Fig. 13(b), driving on

207 roadway Ⅱ proceeded while roadway Ⅰ was filled. This process continued until the driving and filling in stage 2 was

208 finished.

209   Driving and filling in stage 3: the coal pillar on the right-hand side of roadway I was mined, resulting in the formation

210 of roadway a. Meanwhile, 3 m wide coal pillars were established on both sides of roadway a. Afterwards, as shown in Fig.

211 13(c), driving on roadway b proceeded while roadway a was filled. This process continued until the driving and filling in

212 stage 3 was finished.

213   Driving and filling in stage 4: the coal pillar on the left-hand side of roadway I was mined, resulting in the formation of

214 roadway A. Meanwhile, 3 m wide coal pillars were established on both sides of roadway A. Afterwards, as shown in Fig.

215 13(d), driving on roadway B proceeded while roadway A was filled. This process continued until the driving and filling in

216 stage 4 was finished, as shown in Fig. 13(e).

217 **7.3 Application effect analysis**

218   At present, the 3101 working face has been advanced for 170m. To thoroughly study rock strata movement and

219 deformation rules at Changxing coal mine, ground movement observation stations were built in corresponding position

220 above the working face. Surface movement observing proceeded from January 5, 2014 to December 5, 2014.

221   According to the analysis of the surface monitoring data, the accumulated maximum subsidence at the surface

222 monitoring point is 15mm and the maximum horizontal deformation is 0.8 mm/m. These are both controlled within Grade I

223 deformation specified by State Bureau of Coal Industry. The analysis indicated that the ground basically had no obvious

224 deformation after the implementation of the roadway backfill method at 3101 working face.

225   When the roadway backfill method was adopted in Changxing coal mine, the coal recovery ratio approached 70% and

226 the compression ratio was more than 90%. Also, the loess and aeolian sand treatment capacity reached 718,000 t/a; with a

227 large amount of solid mine wastes being used as backfill materials for filling goaf. The overlying strata of the goaf is well

228 supported to prevent strata movement and surface subsidence, thereby protecting ecological environment at the local mining

229 area. Successful application of roadway backfill method in Changxing coal mine may provide some references to other coal

230 mines in the western area for improving coal recovery while protecting the environment.

231 **8 Conclusions**

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

233 following conclusions:

234   (1) The mining rate of the room and pillar method is less than 30%. Meanwhile, the coal pillars creep over time and

235 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, 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 optimise 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 optimised to avoid the added effects of mining-induced stresses.

(5) According to the analysis of the surface monitoring data, the accumulated maximum subsidence is 15mm and the maximum horizontal deformation is 0.8 mm/m, 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%.

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Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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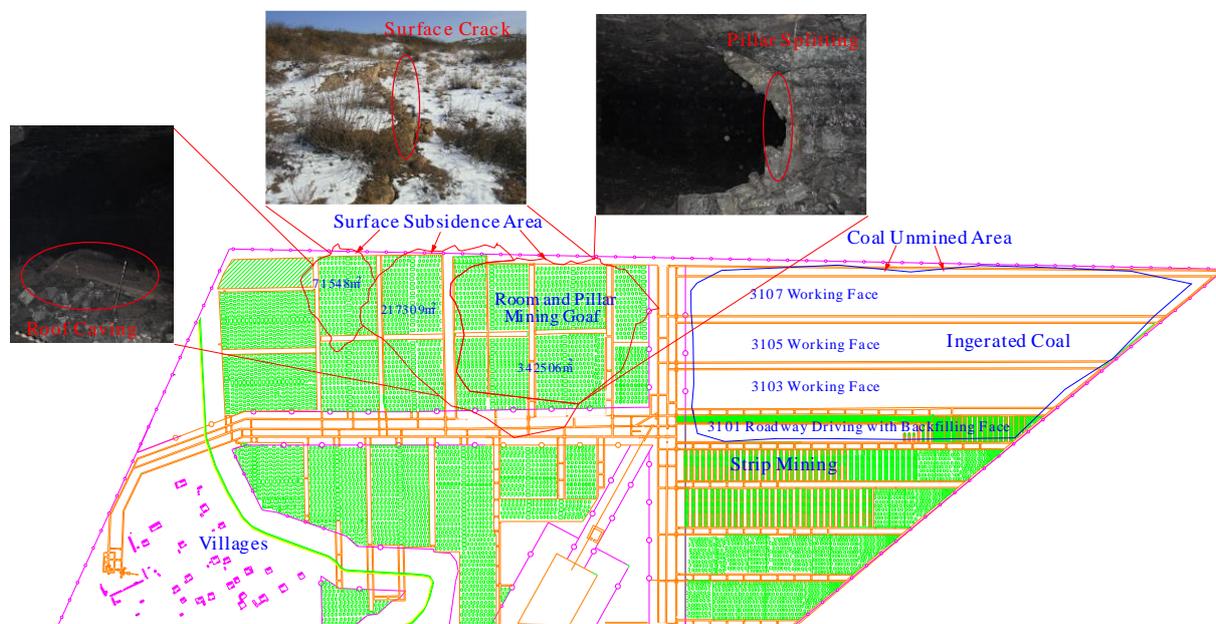
324

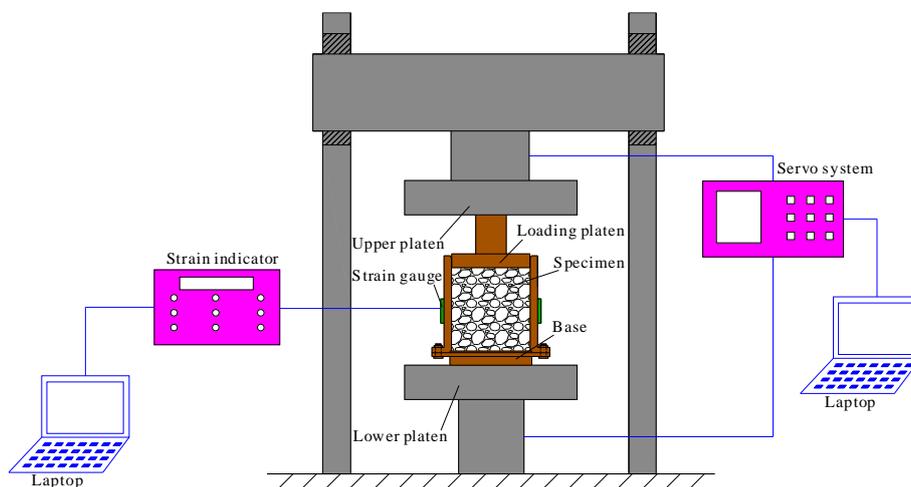
Tables and Figures:

Table 1. Composition of backfill materials (percent by weight).

Sample No.	Aeolian sand	Ratio of 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

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	32	32	2200
Immediate roof	4.5	0.8	1.6	28	28	1600
Coal seam	5.35	0.6	1.2	21	21	1400
Floor	7.6	1.0	1.8	28	28	1600

329

330 **Figure 1.** Surface subsidence induced by room and pillar mining in Changxing coal mine.

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332 **Figure 2.** Schematic diagram of test system.

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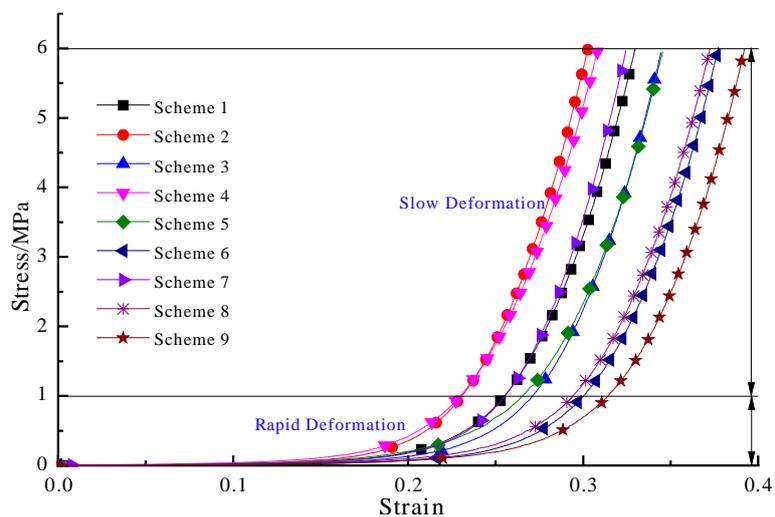
Figure 3. Stress-strain curves of backfill materials.

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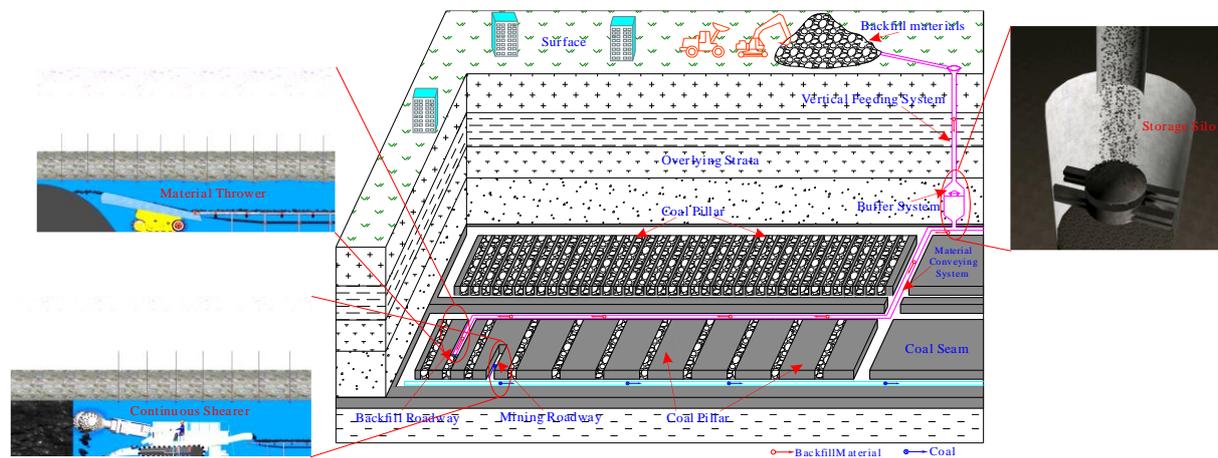
Figure 4. Principle of roadway driving with backfill technique.

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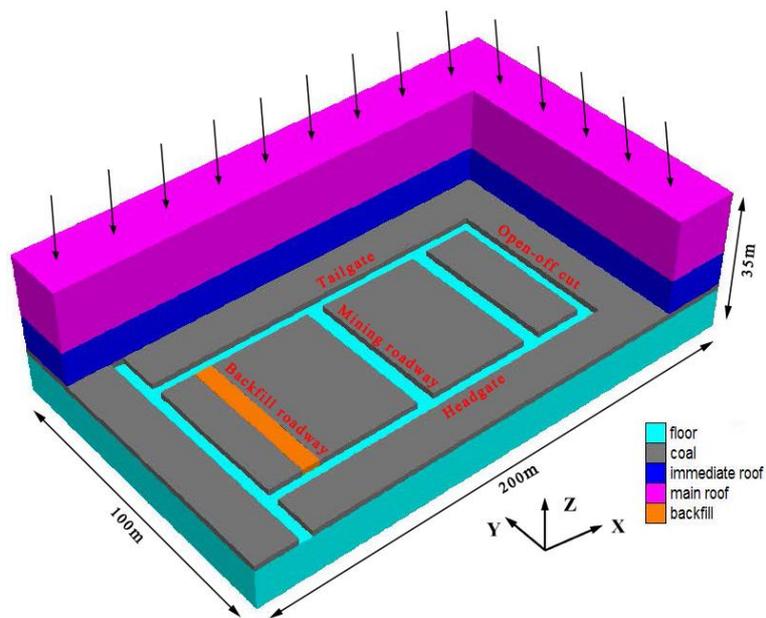
Figure 5. Numerical calculation model.

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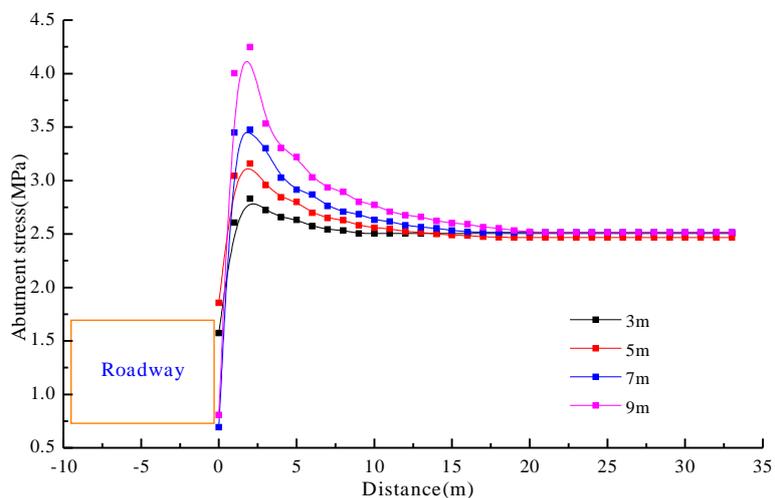
Figure 6. Distribution of abutment stresses on the roadway.
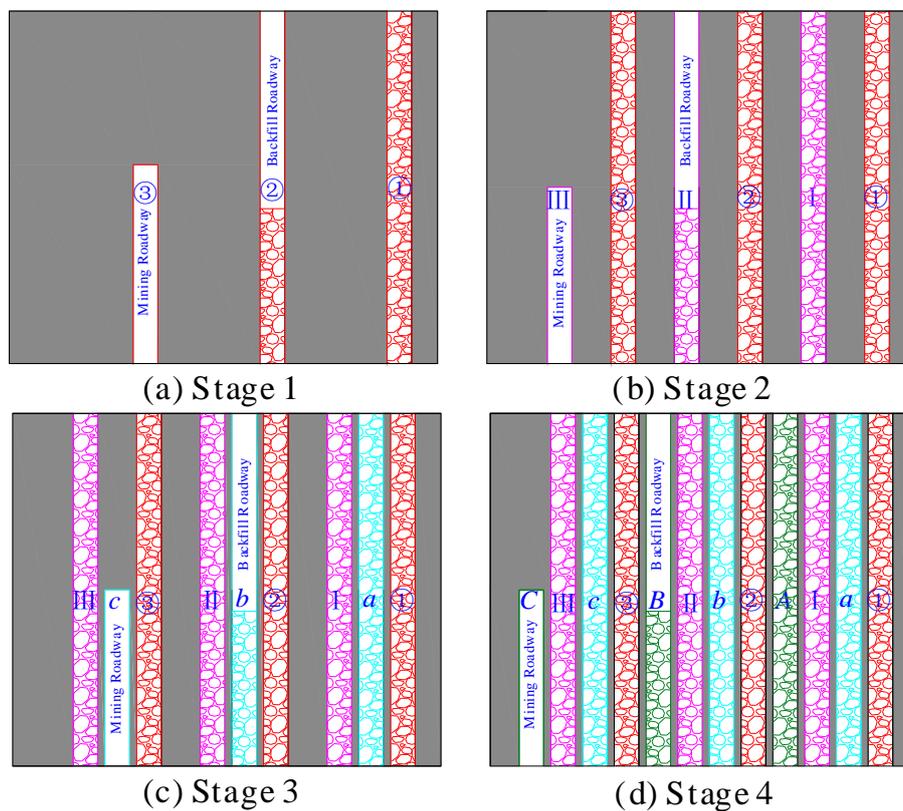
Figure 7. Simulation of driving on multiple roadways.

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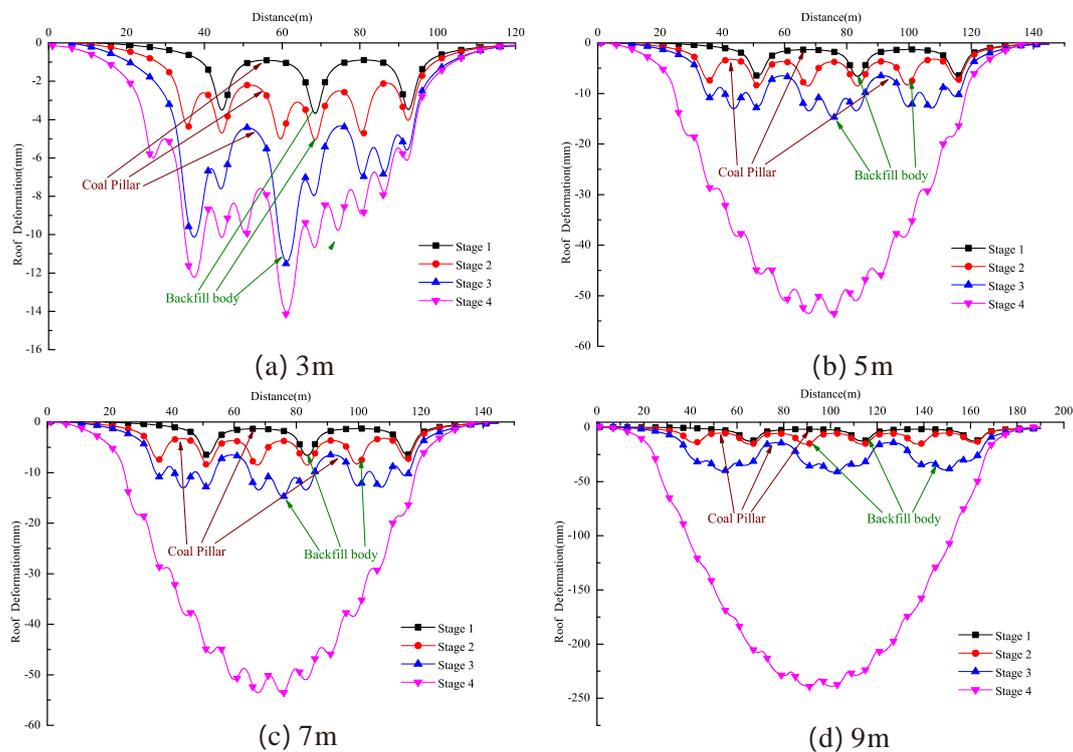
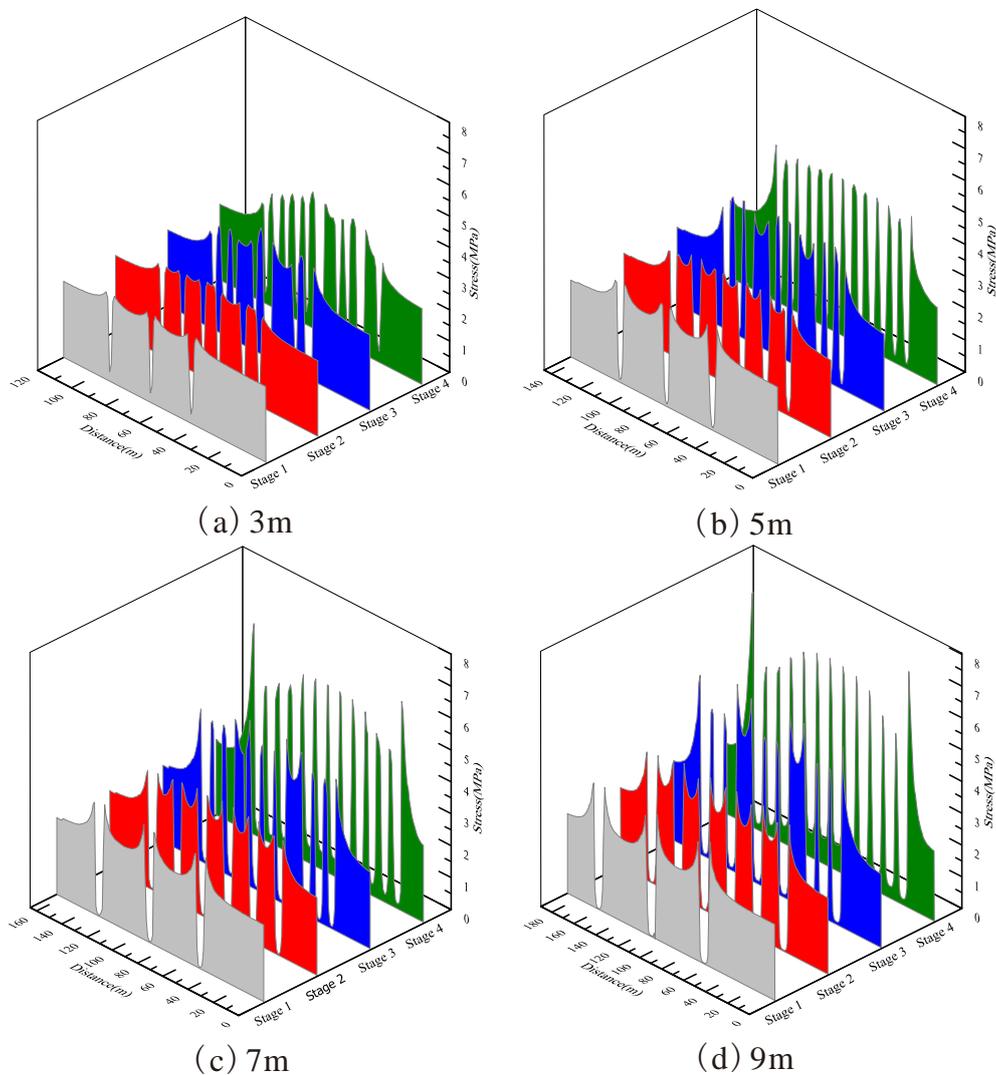


Figure 8. Roof subsidence with different width of roadway.

(a)3m   (b)5m

(c)7m   (d)9m

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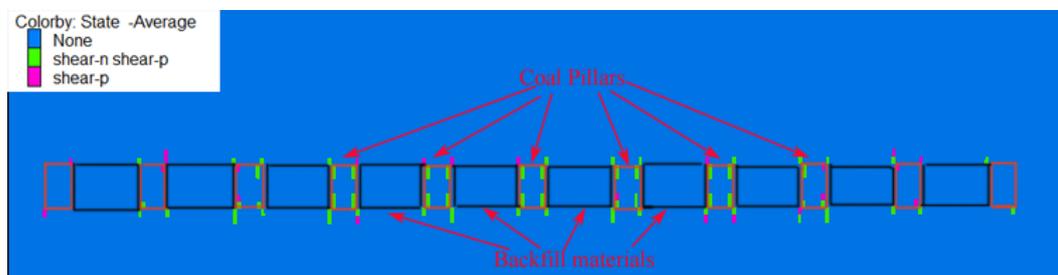
346 **Figure 9.** Stress distributions with different width of roadway.

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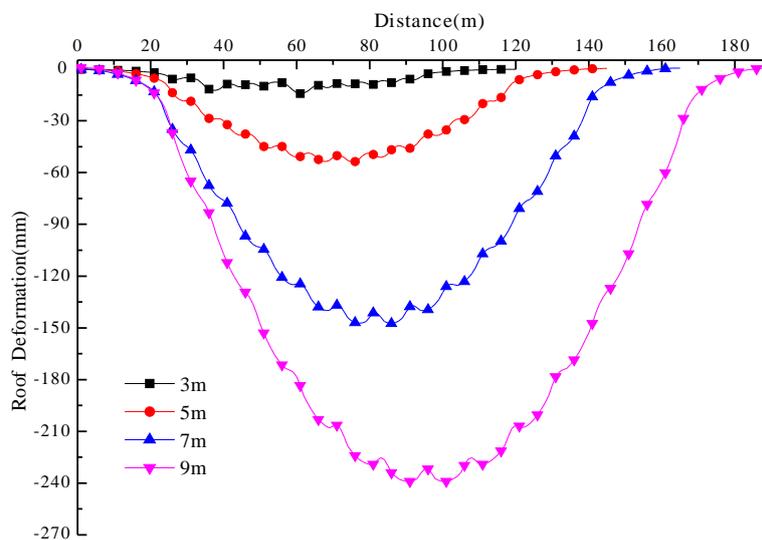
348   **Figure 10.** The plastic zone distribution for a 9 m wide excavation roadway.

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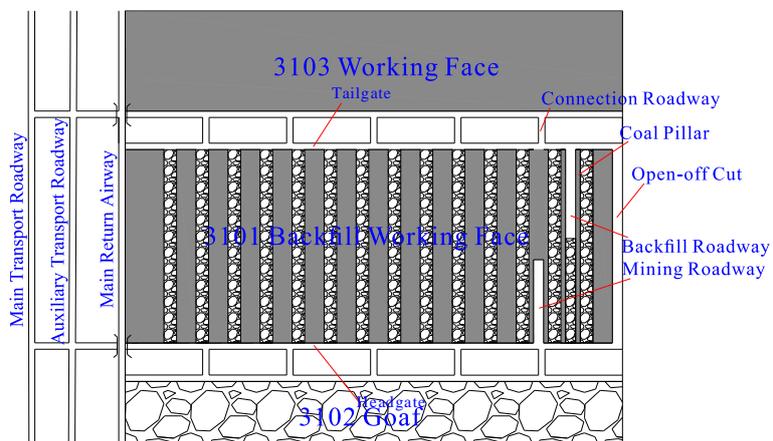
350 **Figure 11.** Roof subsidence after quadratic stabilisation.

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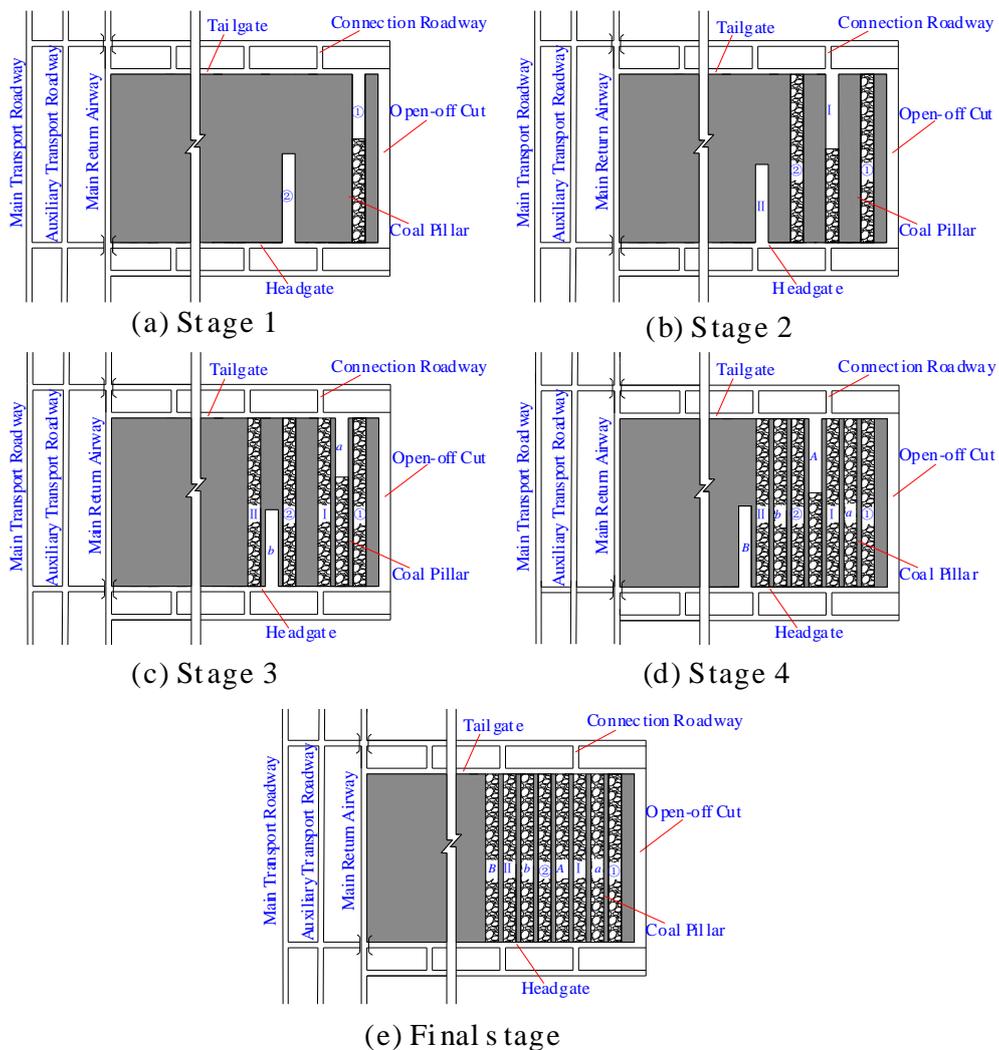
352 **Figure 12.** Layout of the mining system used in the Changxing coal mine.

(e) Final stage

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354 Figure 13. **Design of the driving and filling sequence in the backfill of the driving roadway during mining.**