A novel short-wall caving zone backfilling technique for controlling mining subsidence

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Abstract
Mining-induced voids are the main circulation pathways for underground fluids such as water and coalbed methane. The collapse of these voids transmits to the ground surface, resulting in subsidence and building collapse. Accordingly, effective and feasible solutions are needed to control surface subsidence. In this study, a novel technique of void filling in the short-wall caving zone was proposed to better control surface subsidence in thin coal seam mining. The width of the working face plays a key role in the proposed technique. A maximum surface subsidence value was predicted using numerical simulation and physical simulation experiments with different working face widths. The results indicate that the appropriate working face width should be less than 50 m for the studied coal mine. In this example, the surface subsidence coefficient was less than the standard value for initial damage to rural structures. Both advancing speed and productivity of the working face were achieved using the proposed technique because the filling and mining processes were conducted simultaneously on different faces. The results suggest that surface subsidence during thin coal seam mining could be controlled using the proposed technique. This technique can also help mitigate mining-induced water inrush and gas leakage disasters by filling voids.

KEYWORDS
backfilling technology, key stratum, short-wall caving zone, surface subsidence, void filling

1 | INTRODUCTION

For coal resources that are buried beneath farmland, villages, and surface structures, conventional longwall mining techniques without filling the mined-out area would damage surface infrastructure and cultivated land resources. However, abandoning these underground resources also places economic pressure on the planning and development of coal enterprises. Therefore, a better technique is urgently needed to effectively control mining-induced surface subsidence and ensure sustainable development of coal resources. Numerous studies have attempted to address this problem1-6 and to estimate the influence7 with different methods.8 Backfilling mining technology is a well-known technique for controlling surface deformation widely used in China and other Asian countries,9 Poland,10,11 and Australia12-15; it solves the problem of gangue accumulation,16,17 improves the resource recovery rate,18,19 controls surface subsidence,2,20 and protects buildings from collapse damage.12,20 To prevent rock deformation and control surface subsidence, mine backfilling technology delivers material (including fly ash, gangue, or a compound slurry) to the gob area,14,21 bed separation
zone, bed separation, and caving zone. These methods consist of gob filling, bed separation zone grout injection, pier-column backfilling, and caving zone filling. Recently, gob filling mining technology has been widely utilized in China with a high filling rate and small surface subsidence.

The technique was used in thin coal seam mining, the total filling cost would be quite high because of the high cost of drilling surface boreholes.

The Tianjia Coal Mine is located in the Linzi District of Zibo City, Shandong Province, China. The ground surface of the mining area is mostly covered with farmland and villages. The category of coal resources buried in the Tianjia Coal Mine is coking coal, which has a low level of impurities and a high calorific value. Almost all the coal in this deposit has been mined out, except for beneath the villages and farmland. If the rest of the resources were left in the deposit, the mine would face resource exhaustion and could even halt production. However, if mining continues it may result in house collapse and damage to farmland and irrigation facilities. Owing to economic and social issues such as the expense of village relocation, national environmental requirements, and ecological regulations, it was critical to implement feasible, economic, and effective measures to mitigate mining-induced surface subsidence. Zhu et al. proposed a pier-column filling technique, which was used to control mining-induced surface subsidence in Wangzhuang Coal Mine by grouting pier columns in the goaf. The technique is suitable for coal mines with a hard roof, because the time is required for the pier column to become stable and function normally before the roof appears heavy deformation. Given the soft roof, the pier-column filling technique is not appropriate to use in the Tianjia Coal Mine.

Based on the analyses mentioned previously, a new backfilling mining technique, filling mining in the short-wall caving zone, is proposed in this study. This technique is designed to prevent deformation of the main roof and to reduce overburden subsidence by timely filling of the caving zone. The feasibility was analyzed numerically and experimentally, and the technique was applied in the Tianjia Coal Mine for its technical feasibility and economic benefits.

2 | MATERIALS AND METHODS

2.1 | Description of the proposed technique

The filling mining in the short-wall caving zone technique was designed and implemented based on the key stratum (KS) hypothesis. The thick and hard rock stratum in the overburden that controls the whole and partial strata is defined as the KS. The rock strata controlled by the KS will deform and break, keeping pace with the KS. There are generally one or more key strata in the overburden of a mining panel. The KS located closest to the ground surface is defined as the primary key stratum (PKS) and controls strata from itself up to the ground surface. The PKS also only occurs once in the overlying strata. When the deepest KS breaks, the strata will break simultaneously, leading to bed separation underneath the next KS. In addition, when the PKS breaks, the entire overburden will deform simultaneously without the formation of bed separations. On the other hand, the deformation and subsidence of the overburden will be controlled if the main roof does not break; filling mining in the short-wall caving zone is based on this principle. The technique is implemented by first arranging and implementing a double roadway layout for the mine’s working face according to the designed width, with a 3-5 m coal pillar left between the two faces. Then, the first working face is excavated, as shown in Figure 1A, a sealing wall is built and a filling mouth is left when the working face advances to the designed mining distance, with a profile as shown in Figure 1D. Filling material delivered to the mine is stirred evenly in the filling station built at the ground surface and injected into the caving zone via filling pipelines. During the filling process, the next working face is then excavated and advances, as shown in Figure 1B. These steps are repeated continuously, as shown in Figure 1C.

2.2 | Design principle

To maintain the integrity of the main roof, it is necessary to design the width of working face to ensure that its hanging length is less than its maximum span. The filling rate was also considered, which is closely related to the expansion characteristics of filling material. The filling slurry must flow and fill almost the whole caving zone to reduce the subsidence space of the main roof. The compression rate of the filling material is also important because the volume of the filling body should be stable enough over time to passively support the main roof. The surface subsidence coefficient should also be less than 0.15 to ensure that rural structures are suitable for habitation. In addition, the coal inclination angle is an
important factor that affects the flow direction of the filling slurry in the caving zone. Therefore, during the implementation of the proposed method, uphill mining is necessary to guarantee that the filling slurry will fill the caving zone spontaneously.

2.3 Characteristics of the filling material

The filling material was a mixture of filling slurry, gangue (from coal mines), and the admixture of calcium oxide and aluminum oxide. Furthermore, filling slurry was composed of fly ash, plaster, lime, and cement. After the slurry was mixed with the admixture, the mixture would be initially set in 5 hours, and almost completely solid in 14 hours. During the mixing process, air bubbles would be produced, which could not escape from the slurry and could not merge with other bubbles, but just stayed where they were suspended. Consequently, the volume of the solidified slurry would quickly expand, even at an expansion ratio of 3% after 14 days.

Filling material should also be able to support the weight of the overburden up to the surface, with the slurry's volume change within the requirement. To determine the loading range in the test, the gravity stress of overburden up to the ground surface in the Tianjia Coal Mine was calculated, as shown in Formula (1),

$$\sigma_z = \sum_{i=1}^{n} \gamma_i h_i$$  \hspace{1cm} (1)

where $\sigma_z$ is the gravity stress of overburden up to the ground surface, $\gamma_i$ is the volumetric weight of every rock stratum, as shown in Table 1, and $h_i$ is the thickness of every rock stratum, as shown in Figure 3.

After calculation from Formula (1), the gravity stress of overburden up to the ground surface was determined to be 3.7 MPa. Therefore, the loading range should include 3.7 MPa.

A filling slurry was mixed with gangue from the Tianjia Coal Mine to make a test slurry sample. Two sets of tests were conducted in the testing machine (Electronic Universal Testing Machine, produced by MTS Industrial System co. LTD.) to obtain the compression rate, which varied with time and axial pressure (Figure 2). The results indicated that the compression rate was 6.2% when the maximum axial pressure

| Lithology            | Volumetric weight (N m$^{-3}$) | Bulk (GPa) | Shear (GPa) | Cohesion (MPa) | Friction (°) | Tension (MPa) |
|----------------------|--------------------------------|------------|-------------|----------------|--------------|---------------|
| Fine sandstone       | 27 000                         | 10.00      | 6.50        | 10.00          | 36           | 4.20          |
| Siltstone            | 25 500                         | 6.70       | 4.00        | 7.50           | 30           | 3.50          |
| Medium sandstone     | 23 000                         | 13.56      | 9.75        | 2.40           | 36           | 1.40          |
| Igneous rock         | 22 500                         | 12.93      | 9.13        | 3.40           | 35           | 1.50          |
| Mudstone             | 21 000                         | 0.60       | 3.00        | 5.00           | 25           | 1.80          |
| Coal                 | 13 000                         | 1.30       | 1.50        | 3.20           | 28           | 1.20          |
was 12 MPa after one day, and 1.3% after 7 days. Therefore, the compression rate of the filling material was small enough to meet the 15% requirement.\(^{22}\)

### 3 | ANALYSIS OF FEASIBILITY

#### 3.1 | Geological setting

Tianjia Coal Mine is located in Linzi District of Zibo City, Shandong Province, China. Its designed annual productivity is 120 million kilograms. Currently, the mine has only one producing coal seam from 129.5 m to 165.2 m below ground surface, with an average thickness of 1 m, and a coal inclination angle ranging from 5° to 10° (average 6°). The immediate roof rock is a 2.0-m-thick layer of mudstone, the main roof is composite layers of 1.4-m-thick siltstone and 2.0-m-thick fine sandstone, and the immediate floor is a 2.56-m-thick layer of fine sandstone.

#### 3.2 | Theoretical analysis

Key strata in the overburden were identified by a computer program\(^{29}\) (Analysis System for Overburden in Shallow Coal Seam Mining, developed by Laboratory of Rock Movement and Green Mining, China University of Mining and Technology) based on geological data from a borehole in the Tianjia Coal Mine,\(^{30}\) as shown in Figure 3.

The hanging length of the KS is closely related to the working face width: the larger the working face width, the longer the hanging length of the KS. The KS will deform and break if its hanging length exceeds its acceptable maximum span. A model was developed to describe the corresponding relationship between the KS maximum span and the working face width,\(^{35}\) as shown in Figure 4.

This model was simplified into a simply supported beam to visually analyze the breaking interval of the KS. Considering the position of maximum shear stress is at the ends of the beam, the initial breaking interval for each KS was calculated according to the Formula (2) when the maximum stress reached the shear strength of every KS.\(^{36}\)

\[
L_{KS} = \frac{4h\sigma_s}{3q}
\]

where \(L_{KS}\) is the initial breaking interval of the KS, \(h\) is the thickness of KS, \(\sigma_s\) is the shear strength of KS, and \(q\) is the weight of the KS and its load.

The geometric relationship between the initial breaking interval of each KS and the working face width is

\[
a_{KS} = 2\sum h_i \cot \theta + L_{KS}
\]

where \(a_{KS}\) is the working face width corresponding to the breaking of the KS, \(\theta\) is the breaking angle of the KS, and \(\sum h_i\) is the total thickness of the rock strata between the roof and the KS.

The working face widths were calculated which caused the hanging length of the KS exceed its acceptable maximum span when the parameters were \(\sum h_{KS1} = 2\ m\), \(\sum h_{KS2} = 12.4 \ m\), \(\sum h_{KS3} = 35.84 \ m\), \(\sum h_{PKS} = 61.44 \ m\), \(\theta = 70^{\circ}\), \(\sigma_{KS1} = 56.3 \ MPa\), \(\sigma_{KS2} = 61.44 \ MPa\), \(\sigma_{KS3} = 12.7 \ MPa\), \(\sigma_{PKS} = 19.4 \ MPa\), \(q_{KS1} = 3.64 \ MPa\), \(q_{KS2} = 3.38 \ MPa\), \(q_{KS3} = 2.84 \ MPa\), and \(q_{PKS} = 2.22 \ MPa\) (Table 2).

According to Table 2, it could be figured out that only KS1 broken and the bed separation zone only appeared at the interface of the KS1 when the working face width was less than 50 m. This analysis preliminarily suggests that filling mining in the short-wall caving zone is a feasible method to prevent surface subsidence, and its feasibility was further studied using simulation experiments.

#### 3.3 | Numerical simulations

Based on theoretical analysis, the bed separation value was simulated for different working face widths using discrete element numerical simulation software, Universal Distinct Element Code (UDEC3.0), developed by Itasca Consulting Group. To simplify the problem, a series of 2D numerical models were built, and the mechanical parameters used in the simulation were obtained from laboratory
testing on the strata borehole samples, as shown in Figure 3 and Table 1. Based on the KS hypothesis, the key strata dominate the overall breakage and movement of the whole strata. Therefore, the key strata in the models had comparable thickness and stiffness with the real scenario, whereas the soft strata between key strata were simplified to have the same property. The horizontal length of the model was 700 m, and the height was 200 m. The boundary displacement was fixed in the simulation, as the left and right boundaries were constrained to one side, and the lower boundary was constrained to two sides as shown in Figure 5. The Mohr-Coulomb criterion was used for the constructive relationship.

Dilatation of the rock after the collapse was not considered in the numerical simulation. Numerous field measurements have demonstrated that the long-term surface subsidence is approximately equal to mining height in the eastern part of China, as a large proportion of the strata in the overburden are soft rock strata such as mudstone and clay stone, that formed in the Cenozoic Era. Therefore, the results of the numerical simulation could be considered equivalent to long-term subsidence for this area.

| Order | Thickness (m) | Depth (m) | Lithology      | Position |
|-------|---------------|-----------|----------------|----------|
| 47    | 19.5          | 19.5      | Topsoil        |          |
| 46    | 29.8          | 49.3      | Sandy conglomerate |      |
| 45    | 25.7          | 75        | Sandy conglomerate |      |
| 44    | 0.6           | 75.6      | Fine sandstone |          |
| 43    | 3.9           | 79.5      | Siltstone      |          |
| 42    | 4.3           | 83.8      | Claystone      |          |
| 41    | 1             | 84.8      | Fine sandstone |          |
| 40    | 3.3           | 88.1      | Claystone      |          |
| 39    | 0.66          | 88.76     | Fine sandstone |          |
| 38    | 8             | 96.76     | Mudstone       |          |
| 37    | 6.1           | 102.8     | Fine sandstone |          |
| 36    | 1             | 103.86    | Siltstone      |          |
| 35    | 1             | 104.86    | Claystone      |          |
| 34    | 6             | 110.86    | Fine sandstone | PKS     |
| 33    | 1.7           | 112.56    | Mudstone       |          |
| 32    | 2.4           | 114.96    | Fine sandstone |          |
| 31    | 0.5           | 115.46    | Siltstone      |          |
| 30    | 2.1           | 117.56    | Siltstone      |          |
| 29    | 1.8           | 119.36    | Fine sandstone |          |
| 28    | 1             | 120.36    | Siltstone      |          |
| 27    | 1.7           | 122.06    | Fine sandstone |          |
| 26    | 0.8           | 122.86    | Claystone      |          |
| 25    | 1.6           | 124.46    | Siltstone      |          |
| 24    | 0.5           | 124.96    | Coal seam      |          |
| 23    | 7             | 131.96    | Siltstone      |          |
| 22    | 4.5           | 136.46    | Medium sandstone | KS3   |
| 21    | 1             | 137.46    | Mudstone       |          |
| 20    | 2.6           | 140.06    | Claystone      |          |
| 19    | 0.66          | 140.72    | Fine sandstone |          |
| 18    | 0.9           | 141.62    | Siltstone      |          |
| 17    | 0.88          | 142.5     | Coal seam #4   |          |
| 16    | 2.6           | 145.1     | Fine sandstone |          |
| 15    | 2.6           | 147.7     | Mudstone       |          |
| 14    | 0.5           | 148.2     | Coal seam #4-1 |        |
| 13    | 1.1           | 149.3     | Claystone      |          |
| 12    | 3.4           | 152.7     | Fine sandstone |          |
| 11    | 3.3           | 156       | Siltstone      |          |
| 10    | 3.9           | 159.9     | Igneous rock   | KS2      |
| 9     | 0.9           | 160.8     | Siltstone      |          |
| 8     | 1.2           | 162       | Fine sandstone |          |
| 7     | 0.5           | 162.5     | Mudstone       |          |
| 6     | 2.4           | 164.9     | Siltstone      |          |
| 5     | 2             | 166.9     | Mudstone       |          |
| 4     | 2             | 168.9     | Fine sandstone |          |
| 3     | 1.4           | 170.3     | Siltstone      | KS1      |
| 2     | 2             | 172.3     | Mudstone       |          |
| 1     | 1             | 173.3     | Coal seam #4-2 |        |
Only the working face width parameter was varied in the 11 design schemes (from 30 m to 80 m) at 5-m intervals. An appropriate range of working face widths was obtained by comparing the bed separation values from different schemes and the simulation results, as shown in Table 3.

The results indicate that the first KS would not deform and break when the working face width was less than 50 m, so there is an acceptable range of working face width for the proposed technique. However, the aim is to control subsidence and avoid village relocation, so the surface subsidence coefficient and the reducing subsidence coefficient were also simulated in two groups of scenarios, as shown in Table 4.

In the simulations, the filling process was not conducted after the mining process ended in the first group, but it was conducted in the second group, and simultaneously the adjacent working face began production. The curves of the simulation results are shown in Figure 6.

The surface subsidence coefficient was less than 0.15 in the simulation when the working face width was less than 50 m. It is also observed that the larger the working face width, the greater the surface subsidence coefficient, as shown in Figure 7A. Additionally, the larger the working face width, the smaller the reducing subsidence rate, as shown in Figure 7B.

### 3.4 | Physical simulation

Based on the theoretical analysis and numerical simulation, physical models were also prepared to further study and compare the surface subsidence with and without filling. In these models, the geometric similarity ratio was 1:100; the weight-to-weight similarity ratio was 1:1.5; the stress similarity ratio was 1:150; and the time similarity ratio was 1:10. River sand was used as an aggregate material and mixed with calcium carbonate, and gypsum in specific proportions, as shown in Table 5. Water was then added and the mixture was stirred evenly into a cementing material.

Two models were built, and they were kept identical except that the filling process occurred after the mining process in the first model but did not in the second. The models were 250 cm long, and the working face width was 60 cm in total. Three working faces in the model were excavated consecutively.

The experimental values derived from the model dimensions were converted to actual dimensions using the geometric similarity ratios. The 30-m-wide coal pillars were reserved...
at both sides, and 3-m-wide coal pillars were left between the adjacent working faces. In addition, five surface subsidence observation lines were established on the key strata and the ground surface. Measuring points were arranged on the outer frame of the model, on the surface of every KS, and on the ground surface. The points fixed on strata could move simultaneously with the movement of strata, while those fixed on the frame were stationary throughout the experimental process, as shown in Figure 8A. Every point was made up of a black circle and white square, which can be recognized by the measurement system through identifying the color difference. In the mining process, every excavation step distance was 5 m, and data were collected by a camera at the end of every step. Then, photographs were imported into a digital photogrammetric survey system to monitor the displacement of each KS.

During the monitoring process, the initial distances between stationary points and measuring points were first recorded and saved as initial values. Next, the distances between stationary points and measuring points in the photographs recorded at the end of each excavation step were calculated and saved as changing values. Then, the subsidence after certain steps was obtained by subtracting the initial value from the changing value. Finally, the displacements of each observation line were obtained after each excavation step by fitting the measuring points along lines, which reflects the displacements of the key strata.

During the excavation process, three faces were excavated from left to right sequentially. The results of the experiments with and without filling are shown in Figure 8A and Figure 8B, respectively.

In the results of the filling model, it is observed that there was no deformation in key strata including KS1, KS2, and KS3, as shown in Figure 8A. However, some deformation could be obviously seen in the no-filling model, as shown in Figure 8B. In addition, mining-induced fractures appeared and extended in the overlying strata, nearly to the ground surface, as shown in Figure 8B, with detailed shapes shown in boxes. These phenomena demonstrate that the proposed technique was feasible for controlling strata movement and surface subsidence. To quantitatively compare the results of the

| Group | Width (m) | Number × width (m) | Total width (m) | Filling |
|-------|-----------|--------------------|-----------------|---------|
| 1st Group | 40 | 6 × 40 | 240 | No |
| 50 | 4 × 50; 40 | 240 | No |
| 60 | 4 × 60 | 240 | No |
| 80 | 3 × 80 | 240 | No |
| 2nd Group | 40 | 6 × 40 | 240 | Yes |
| 50 | 4 × 50; 40 | 240 | Yes |
| 60 | 4 × 60 | 240 | Yes |
| 80 | 3 × 80 | 240 | Yes |

| Width (m) | KS1 L (m) | H (mm) | KS2 L (m) | H (mm) | KS3 L (m) | H (mm) | PKS L (m) | H (mm) |
|-----------|-----------|--------|-----------|--------|-----------|--------|-----------|--------|
| 30        | 29        | 900    | ─         | ─      | ─         | ─      | ─         | ─      |
| 35        | 34        | 900    | ─         | ─      | ─         | ─      | ─         | ─      |
| 40        | 38        | 900    | ─         | ─      | ─         | ─      | ─         | ─      |
| 45        | 43        | 900    | ─         | ─      | ─         | ─      | ─         | ─      |
| 50        | 47        | 900    | ─         | ─      | ─         | ─      | ─         | ─      |
| 55        | 53        | 800    | 23.6      | 100    | ─         | ─      | ─         | ─      |
| 60        | 56        | 700    | 11.6      | 100    | 21.2      | 200    | ─         | ─      |
| 65        | ─         | 670    | 57.0      | 667    | 18.0      | 200    | ─         | ─      |
| 70        | ─         | 220    | 33.5      | 220    | 18.0      | 200    | ─         | ─      |
| 75        | ─         | 220    | 29.6      | 220    | 35.0      | 112    | ─         | ─      |
| 80        | ─         | 267    | 65.8      | 267    | 45.0      | 200    | 9.0       | 83     |

Note: where L is the length of bed separation zone, H is the height of bed separation zone.

| Group Width (m) | Number × width (m) | Total width (m) | Filling |
|-----------------|--------------------|-----------------|---------|
| 1st Group 40    | 6 × 40             | 240             | No      |
| 50 4 × 50; 40   | 240                | No              |
| 60 4 × 60       | 240                | No              |
| 80 3 × 80       | 240                | No              |
| 2nd Group 40    | 6 × 40             | 240             | Yes     |
| 50 4 × 50; 40   | 240                | Yes             |
| 60 4 × 60       | 240                | Yes             |
| 80 3 × 80       | 240                | Yes             |
FIGURE 6 A. Width is 40 m; without filling. B. Width is 40 m; with filling. C. Width is 50 m; without filling. D. Width is 50 m; with filling. E. Width is 60 m; without filling. F. Width is 60 m; with filling. G. Width is 80 m; without filling. H. Width is 80 m; with filling.
two models, the subsidence of the ground surface and every KS was collected, as shown in Figure 9.

It is inferred from Figure 9 that the maximum surface subsidence reached 103 mm in the filling model and 875 mm in the no-filling model. The surface subsidence coefficients were 0.103 and 0.875, respectively. It is interesting to note that, as shown in Figure 9A, the KS1 and KS2 above the coal pillars had obvious subsidence inhibition; however, this was not the case in Figure 9B. The reason for this is that the 3-cm-wide coal pillars used in the experimental process failed to bear the total weight of overburden and broke when the caving zones were not filled. The experimental results indicate that filling mining in the short-wall caving zone effectively controlled surface subsidence and therefore could help eliminate the need for village relocation due to mining activities.

4 | CASE STUDY

4.1 | Site description

There are villages and farmland on the surface of the mineable coal seam at the Tianjia Coal Mine. Given the conditions explained in the introduction, filling mining in the short-wall caving zone was applied to three faces: Nos. 40102, 40104, and 40106 in the Tianjia Coal Mine, as shown in Figure 10. The widths of the three working faces were 43 m, 42 m, and 70 m.

4.2 | Filling process

The filling process began after the first working face was completely excavated. The filling process included two stages: filling preparation and filling. Filling preparation occurred at the ground surface, as shown in Figure 11. Water and fly ash were continuously mixed and stirred in an ash cylinder. Second, plaster, lime, and cement were mixed in a mixing tank and stirred continuously into a binding agent. The filling material was prepared by injecting the fly ash slurry and the admixture slurry into the mixing tank and stirring evenly. In the second stage, the filling material was delivered through pipelines to the underground filling area and injected into the caving zone. After the filling process was complete, the filling pipelines were cleared with clean water.

Both the sequence of mining the working faces and the filling sequence of caving zones was, in sequence, No. 40102, 40104, and 40106. The filling results are shown in Table 6.

**Figure 7** A, Surface subsidence coefficient. B, Reducing subsidence rate

**Table 5** The proportion of materials in the physical models

| Strata         | Thickness (cm) | Number of layers | Weight ratio |
|----------------|----------------|------------------|--------------|
|                |                |                  | River sand   | Calcium carbonate | Gypsum | Water |
| Topsoil        | 19             | 10               | 40           | 1                 | 1      | 3     |
| Rock soft      | 85             | 40               | 40           | 7                 | 3      | 3     |
| PKS            | 6              | 1                | 30           | 3                 | 7      | 4     |
| Rock soft      | 21             | 10               | 40           | 7                 | 3      | 3     |
| KS3            | 4.5            | 1                | 30           | 3                 | 7      | 4     |
| Rock soft      | 19             | 10               | 40           | 7                 | 3      | 3     |
| KS2            | 4              | 1                | 30           | 3                 | 7      | 4     |
| Rock soft      | 9              | 4                | 40           | 7                 | 3      | 3     |
| KS1            | 1.4            | 1                | 30           | 3                 | 7      | 4     |
| Immediate roof | 2              | 1                | 40           | 7                 | 3      | 3     |
| Coal seam      | 1              | 1                | 40           | 5                 | 2      | 3     |
| Floor          | 6              | 2                | 40           | 7                 | 3      | 3     |
FIGURE 8  A. Physical model of filling mining in the short-wall caving zone. B. Physical model of mining without filling
For the working faces with widths of 43 m and 42 m, the filling rates were 91.8% and 93.7%, respectively. However, for the working face with a width of 70 m, the filling rate was only 71.5%. This indicates that the working face width should be less than 50 m to obtain higher filling rates. As a result, the width of the next face (40108) will be designed as 50 m for the safety study.

4.3 Results

A survey line was constructed on the corresponding ground surface of the working faces for measuring the dip displacement. A total of 21 points were set on the 625-m-long dip line, with 100 m between base points and at 25-m intervals, as shown in Figure 10.

According to the Chinese standard value for first-class damage to rural structures, the point at which buildings can still be used normally, the surface subsidence coefficient should be less than 0.15, and the dip deformation and horizontal deformation should be greater than or equal to −3.0 mm/m and −2.0 mm/m, respectively, and less than or equal to +3.0 mm/m and +2.0 mm/m, respectively. The ground subsidence, dip deformation, and horizontal deformation from the case study are shown in Figure 12.

After the No. 40102 and 40104 faces were excavated, all three measuring results were within the range of standard values presented above, with maximum surface subsidence reaching 83 mm, and a surface subsidence coefficient of 0.083. The dip deformation and horizontal deformation ranged from −0.64 mm/m to +0.61 mm/m and −0.48 mm/m to +0.60 mm/m, respectively. However, after the third face (70 m width) was excavated, the total surface subsidence and surface subsidence coefficient increased to 186 mm and 0.186, respectively. This is an increase of 103 mm in surface subsidence and exceeds the allowed maximum subsidence coefficient of 0.15. The ranges of dip deformation and horizontal deformation are as follows:...
horizontal deformation were −1.52 mm/m to +1.84 mm/m and −0.64 mm/m to +0.84 mm/m, respectively. Fortunately, the ground surface of the No. 40106 working face is farmland, which is less affected by mining activities, compared with villages that have a larger number of masonry structures. As shown in Figure 12A, the surface subsidence values induced only by mining the No. 40104 and No. 40106 faces were 57 mm and 111 mm, respectively. These values were obtained by subtracting the subsidence induced by mining the No. 40102 face from the total of the first two faces and subtracting the subsidence induced by the first two from the total of the three faces, respectively. This case study demonstrates that filling mining in the short-wall caving zone can control surface subsidence and ensure it does not exceed the standard surface subsidence value when the working face width is less than 50 m for the geological settings at the Tianjia Coal Mine.

Compared with the gob filling technique, the proposed backfilling technique possesses the advantages of high advancing speed and production efficiency due to the mining and filling processes occurring simultaneously on different working faces without interference.

5 | DISCUSSION

Filling mining in the short-wall caving zone is an extension of existing mining techniques. Zhu et al. made a comparison among existing technologies. Strip mining can control surface subsidence well; however, a large proportion of the resource (more than 50%) is wasted in the process. The bed separation zone grout injection technique injects filling material through boreholes from the ground surface to the bed separation zone, which is suitable for single coal seam mining. Traditional gob filling techniques install delivery equipment underground and deliver gangue to the goaf, which solves the problem of gangue pollution, surface subsidence, and even fly ash waste. Given the infrastructure cost and space requirement, gob filling techniques are widely used in thick coal seam mining. Pier-column filling grouts pier columns in the goaf that support the roof after becoming stable to reduce the bed separation zone in the overburden and mitigate surface subsidence during thin coal seam mining. Therefore, a hard roof is an essential condition to avoid the impact of roof collapse during implementation. There are some novel features in the proposed technique. First, only a 3- to 5-m coal pillar is required between two working faces, which provide a significant advantage for the recovery rate, which reached more than 90%. In addition, the filling process is implemented after the whole face is mined out, which guarantees that the filling process proceeds normally regardless of the type of immediate roof. Finally, the filling material is delivered from the ground surface to the caving zone through pipelines passing through the coal shaft, rather than boreholes drilled from the ground surface, and delivery is dependent on gravity rather than a pump station, which reduces the cost. In summary, filling mining in the

| Faces    | Width (m) | Produced coal (t) | Volume of gob area (m³) | Grouting volume (m³) | Filling rate (%) |
|----------|-----------|-------------------|------------------------|----------------------|------------------|
| 40102    | 43        | 11 413            | 8152.3                 | 7638                 | 93.7             |
| 40104    | 42        | 14 954            | 10 681.7               | 9720                 | 91.8             |
| 40106    | 70        | 26 367            | 18 833.9               | 13 466               | 71.5             |

FIGURE 12 A, Surface subsidence. B, Dip deformation. C, Horizontal deformation
short-wall caving zone, which is suitable for thin coal seam mining, is a supplementary method to existing mining techniques, with advantages of high recovery rates, low cost, and simple material delivery.

Admittedly, there are a few limitations should be noticed. Firstly, the proposed technology has been only used in thin coal seam mining. If applied in thick coal seam mining, there would be more costly for filling material, and a wider coal pillar has to be left. Secondly, to spontaneously fill slurry into caving zone under gravity, a certain coal inclination angle and uphill mining method are needed.

6 | CONCLUSIONS

In this study, a novel mining technique, filling mining in the short-wall caving zone, was proposed to control surface subsidence by filling voids in the short-wall caving zone with slurry. The width of the short walls needs to be designed to ensure the integrity of the main roof. After filling, a bearing structure composed of the filled bodies and KS (generally the main roof) can form to control deformation and breakage of the overburden. Three methods, based on the geological conditions of the Tianjia Coal Mine, involving theoretical analysis, numerical simulation, and physical simulation were employed to study the feasibility of the proposed technique. Furthermore, a case study verified its capacity to control surface subsidence in short-wall mining.

Simulations showed that the main roof would not deform and break when the working face width was less than 50 m and the corresponding surface subsidence coefficient was also less than 0.15, which ensures normal functions of buildings. The application of the proposed technique in the Tianjia Coal Mine suggests that filling mining in the short-wall caving zone can be used to control surface subsidence in thin seam coal mining. Removing the need for villages to relocate is an important economic advantage of this novel backfilling method. This technique has been tested in thin seam coal mining, it is believed that mining engineers could utilize the technique to reduce the surface subsidence when mining coal seams under buildings and structures.

It is a complex issue to mitigate mining-induced surface subsidence by controlling strata movement and deformation. The proposed technique is only studied and tested in thin coal seam mining in this paper. Further study on the application of this technique in thick coal seam mining is needed, such as the reserved coal pillar width, coal inclination angle.

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CONFLICT OF INTEREST

None declared.

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