IN THE FIELD

Monitoring and measurement analysis of key indexes for the implementation of mining, dressing, backfilling, and controlling technology in coal resources—A case study of Tangshan Mine

Zhang Qiang1 | Kang Yang1 | Jixiong Zhang1 | Yin Wei2 | Xianwei Liu1 | Zhongya Wu1 | Weijian Song1 | Xu Xiling3

1Key Laboratory of Ministry of Education for Deep Coal Resource Mining, School of Mines, China University of Mining & Technology, Xuzhou, China
2Faculty of Transportation Engineering, Huaiyin Institute of Technology, Huai'an, China
3Tangshan Mining Company, Kailuan Group, Tangshan, China

Correspondence
Zhang Qiang and Jixiong Zhang, Key Laboratory of Ministry of Education for Deep Coal Resource Mining, School of Mines, China University of Mining & Technology, Xuzhou 221116, China. Emails: leafkky@163.com (ZQ); zjxiong@163.com (JZ)

Funding information
This study was supported by the National Natural Science Foundation of China (52174134), the National Natural Science Foundation of China (51904110), and the Fundamental Research Funds for the Central Universities (2021GJZPY12)

Abstract
Based on the mining, dressing, backfilling, and X technology framework, we proposed the key operation indexes by exploring the principle, system, and integrated process of “mining, dressing, backfilling, and controlling” technology. After that, the index monitoring method was established to further analyze the change law of key indexes and implementation effects of “mining, dressing, backfilling, and controlling” technology. The mining engineering of Tangshan mine showed that the “mining, dressing, backfilling, and controlling” technology solves the problems of gangue discharge, construction protection, and safe mining of compressed coal resources. The vertical feeding capacities and filling capacities are 337,171 and 422,428 t/year, respectively. The stress change in the filling body is consistent with the dynamic roof subsidence, with a compacting ratio of 81.3%. The average filling mass ratio (1.28) is greater than the design value (1.2). The maximum ground subsidence is 49 mm, and the deformation of the structure is controlled within the range of Level I. The research result provides evidence for the deepening of the theoretical and technical researches of “mining, dressing, backfilling, and X.” It also provides a technical reference for mines with similar geological conditions and engineering problems.

KEYWORDS
“mining, dressing, backfilling, and control” technology, index analysis, monitoring system, strata control

1 INTRODUCTION

Building green mines are imperative for developing the green mining industry.1,2 It is necessary to realize the development of near-zero ecological damage and the use of near-zero pollutant emissions from the source of innovative mining methods.3,4 Mining, dressing, backfilling, and X5 is typical representative of green mining technology. It is used for coal mining, gangue separation, and backfilling on-site, while...
simultaneously achieving multiple goals including ground subsidence control, hard roof control, ecological environment protection, the simultaneous mining of coal, and its associated resources corresponding to the engineering requirements.

In the “mining, dressing, backfilling, and X” technology, the mining focuses on reducing the exploitation of gangue by the design of mining method. The mining can be the exploitation of unconventional protective layers, realizing the anti-reflection and pressure relief. It can also be the orderly mining of coal seams, focusing on the supply balance of coal mining excavation succession production organization and market to real-time changes in the demand for different coal seams. The dressing may refer to the rough separation of gangue before underground separation. The gangue rate is reduced as much as possible to assist the running coal separation system on the ground. The dressing can also be completed gangue separation to achieve clean coal production underground. Traditionally, the backfilling realizes the strata control effect, including solid backfill (drift dumping, general mining dumping, and full-section dense backfilling), paste, superhigh water, and cemented backfilling mining. Under the current background, backfilling focuses on waste-free production and near-zero emissions. Backfilling and caving methods are used to guarantee production capacity, thus realizing gangue backfilling. X is relevant technology determined by specific engineering requirements, such as no pillar gob-side roadway retaining and gas drainage. The X is integrated with mining, dressing, and backfilling using different technical connotations to form a diversified “mining, dressing, backfilling, and X” system. After that, multiple forms are achieved to implement the green mining concept in the development of near-zero ecological damage and the utilization of near-zero pollutant emissions.

The “mining, dressing, backfilling, and X” is an integrated technical system, its implementation effect needs to be evaluated from multiple subsystems, and each subsystem's evaluation index and monitoring method are different. At present, scholars have done a lot of researches on index monitoring of filling mining system. Zhang et al. monitored and analyzed the deformation modulus of filling gangue, the stress of filling body, and the roof subsidence through indoor and field experiments. Zhang et al. installed roof monitor and corresponding sensors inside the backfill to monitor roof subsidence and backfill stress; Tang analyzed the feasibility of the CORS system for surface subsidence monitoring. The above research contents provide technical support for this paper.

Taking Tangshan Mine of Kailuan Group Co., Ltd. as an example, this paper systematically introduces the principle, system, integrated process, key indicators of operation, and monitoring methods of the “mining, dressing, backfilling, and control” technology, and establishes an indicator monitoring system for the integrated operation of the “mining, dressing, backfilling, and control.” Through monitoring, the implementation effect indicators of the “mining, dressing, backfilling, and control” technology are reflected, including feeding capacity, gangue sorting capacity, advanced abutment pressure, roof dynamic subsidence, and filling body stress, and further analyzes the implementation effect characteristics and basic laws of the “mining, dressing, backfilling, and control” technology. It provides a basis for the deepening of theoretical research and technology development and upgrading of “mining, dressing, backfilling, and X,” and provides technical reference for mines with similar mining geological conditions and engineering problems.

2 | SURVEY OF “MINING, DRESSING, BACKFILLING, AND CONTROL” TECHNOLOGY

2.1 | Basic principles

The “mining, dressing, backfilling, and control” technology is a green mining technology that integrates technologies such as coal mining, coal gangue separation, and filling, and aims to control the breaking of key strata and reduce surface subsidence. The technical principle is to apply the coal backfilling technology for not raising gangue from the well after an organic combination of coal backfilling mining at the working face and underground gangue separation (Figure 1). Meanwhile, we realize the controls of surface subsidence, hard roof, and stope pressure corresponding to engineering requirements are realized by optimizing the backfilling mining method, the precise proportioning of backfill materials, the coordinated backfilling, and mining.

2.2 | Main system

The main system consists of ground solid waste treatment and transportation, vertical feeding, underground coal gangue separation, backfilling mining, and system operation monitoring (Figure 2).

(1) Ground solid waste treatment and transportation system

In the ground solid waste treatment and transportation system, the ground wastes are processed and transported, ensuring the continuous supply of backfilling materials.
The current engineering practice process can be divided into three methods according to the source, type, and possibility of screening and crushing of filling materials:

a. The backfilling materials are the gangue dumps accumulated on the surface. The crushing stations are arranged near the gangue dumps where the gangue is crushed, screened, and transported underground.

b. The backfilling materials are gangue and fly ash (loess, river sand, etc.). After crushing and screening, the mixture of gangue and fly ash is transported underground.

c. The backfilling materials are gangue, fly ash, water, and additives. The gangue crushed to a certain particle size is made into cement or paste according to the specified ratio and pumped underground through the pipeline.

(2) Vertical feeding system

After treatment of ground wastes, the crushed gangue is transported from the ground to the underground for backfilling operations through the vertical feeding system. The backfilling materials are fed in the forms
of newly excavated wells, existing air shafts, auxiliary inclined shafts, and newly excavated boreholes.\textsuperscript{15}

(3) Underground coal gangue separation system

The current underground roughing methods consist of a new jig, cyclone, heavy medium shallow slot, moving sieve jig, and TDS sorting.\textsuperscript{16} Different separation systems have different applicable conditions, advantages, and disadvantages.

(4) Backfilling mining system

The working face backfilling is to deal with the gangue, thus reducing the strength of strata behaviors and controlling the movement of overlying strata. According to different engineering requirements, the layout forms of the backfilling system are divided into:

a. complete mining and complete backfill of gob;
b. complete mining and partial backfill of gob;
c. partial mining and partial backfill of gob;
d. partial mining and complete backfill of gob.

(5) System operation monitoring

After monitoring vertical feeding, underground coal gangue separation, backfilling mining, surface deformation, ground solid waste treatment, and transportation, the data are quantitatively analyzed by related software equipment to reflect the “control” effect at last.

2.3 Key equipment and integrated technology

The “mining, dressing, backfilling, and control” green mining technology depends on backfilling mining, underground coal gangue separation, and working face monitoring equipment. The backfilling mining equipment consists of a coal mining machine, scraper conveyor, backfilling hydraulic support, multi-hole bottom discharge scraper conveyor, and compacting mechanism. The gangue separation equipment is determined by specific sorting methods, including gravity, jig, and heavy medium sorting. The working faces are monitored by a dynamic roof, backfill stress, and filling mass ratio equipment.

The underground coal gangue separation system is organically integrated with the existing backfilling mining system. The gangues from underground gangue separation and ground gangue dump are transported to the working face of backfilling mining through the relevant line. The coal from the working face is shipped out in the original transportation system. After a scientific backfilling operation, the backfill material can effectively control the ground pressure, roof collapse, and surface subsidence.\textsuperscript{17,18}

3 OPERATION CHARACTERISTICS AND CONTROL EFFECT OF “MINING, DRESSING, BACKFILLING, AND CONTROL” TECHNOLOGY

3.1 Operation characteristics of “mining, dressing, backfilling, and control” technology

As one of the representatives of the integration of coal mining, gangue separation, and solid materials backfilling, the “mining, dressing, backfilling, and control” technology has different operating characteristics from the conventional underground production system. The specific manifestations are described as follows:

(1) System composition

The “mining, dressing, backfilling, and control” can be decomposed into coal mining, separation, and backfilling systems based on system composition. Massive subsystems lead to a complex composition of the entire system.

(2) System operation and organization

The scientific implementation of “mining, dressing, backfilling, and control” requires coordination among equipment operation, personnel organization, and technological processes of different subsystems. The system has complicated operating links.

(3) System engineering design

The core technical parameters of the system maintain an internal correlation: feeding and gangue storage capacities, separation and transportation capacities, total underground transportation and backfilling capacities, and backfilling and coal mining capacities.

(4) Evaluation of system effect

The effect of system implementation can be evaluated based on the total amount of filling materials in the goaf. It is equal to the sum of surface feeding and underground sorting. The more total filling amount leads to the denser filling body and the better filling effect; otherwise, the filling effect is worse.
3.2 Operation effect control of “mining, dressing, backfilling, and control” technology

In the integration process of coal mining, gangue separation, and solid materials backfilling, various systems in the mine cooperate, which are independent and inherently related. The change law of dynamic index for system operation can be analyzed through the system operation monitoring system. In the entire process of “mining, dressing, backfilling, and control,” different system monitoring indexes interact with each other to reflect the effect of “control” according to the comprehensive evaluation of indexes.\textsuperscript{19}

The ground gangue treatment and separation systems must meet the requirements of underground filled mass and speed to better reflect the effect of “control,” providing filling materials for filling surface. The coal mining system should not be interacted with the filling system to ensure the orderly operation of mining and backfilling systems. The backfilling system must cooperate with other systems. In the backfilling system, the compacting mechanism is used to maximize the density of filling materials.\textsuperscript{20-23}

4 Key operating indices and monitoring methods

4.1 Key operating indices

Key operating indexes include surface subsidence value, vertical feeding mass, totally filled mass, sorting gangue quality, dynamic compacting ratio, filling mass ratio, dynamic factor, backfill stress, periodic weighting step, advance abutment pressure, dynamic roof subsidence, and secant modulus. The key indicators are shown in Figure 3.

In the entire backfilling mining implementation process, there is an inherent dynamic relationship between the operating indices.

The totally filled mass can be expressed as Equation (1).

\begin{equation}
M = M_0 + M_1
\end{equation}

where $M$ is the totally filled mass; $M_0$ is the vertical feeding quality; $M_1$ is the sorting gangue quality. $M_1$ can be calculated by Equation (2).\textsuperscript{15}

\begin{equation}
M_1 = \sum_{i=1}^{n} J_i \times \omega \times \eta_1 + M_2 \times \omega \times \eta_2
\end{equation}

where $M_2$ is the gangue mass at the working face; $\omega$ the proportion of gangue; $J_i$ the tunneling coal gangue ($i = 1, 2, 3...$); $\eta_1$ and $\eta_2$ are the sorting coefficients of tunneling and coal flow gangue, respectively.

The filling mass ratio $\eta$ is equal to the mass ratio of solid backfill material to mined raw coal (Equation 3).

\begin{equation}
\eta = \frac{M}{m_0} = \frac{\rho_c \lambda}{\rho_0}
\end{equation}

where $m_0$ is the mass of mined raw coal; $\rho_0$ the density of raw coal ($\text{kg/m}^3$); $\rho_c$ the density of solid backfill material after compaction ($\text{kg/m}^3$); $\lambda$ the holding ratio of the solid backfill material, which is determined by $m_k$ (the roof subsidence in advance) controlled by geological conditions.

\begin{equation}
\lambda = \frac{h - m_k}{h}
\end{equation}

where $h$ is the mining height (m).

According to Ref.\textsuperscript{24} we obtain the relationship between the filling mass ratio $\eta$ and the compacting rate $\phi$. 

\[ \text{FIGURE 3 Monitoring system of key operating indices} \]
\[ \eta = \frac{\lambda \rho_1}{\rho_0 (1 - \varphi d_{\text{max}})} \]  

(5)

where \( \rho_1 \) is the natural density of solid backfill material (kg/m\(^3\)); \( d_{\text{max}} \) is the maximum compacting deformation of solid backfill material.

The filling rate is equal to the ratio of the final height to the actual mining height of compacted backfill materials after the overburden is fully settled.

\[ \varphi = \frac{h - (d_{\text{max}} + m_x + m_q)}{h} \]  

(6)

where \( m_q \) is the underfilling height of backfill materials. According to the definition of compacting ratio, we derive the dynamic compacting ratio \( \varphi_d \).

\[ \varphi_d = \frac{h - h_d}{h} \]  

(7)

where \( h_d \) is the dynamic roof subsidence (mm), including the roof subsidence in advance, the underfilling height \( m_q \), and compression height of filling material \( d \) of backfill materials.

\[ h_d = d + m_x + m_q \]  

(8)

In the roof subsidence process, Equation (9) is used to express the relationship between the backfill stress \( \sigma \) and the secant modulus \( E \).

\[ E = \frac{\sigma(h - m_x - m_q)}{d} \]  

(9)

According to the equivalent mining height theory, it can be known that

\[ h_x = d_{\text{max}} + m_x + m_q \]  

(10)

where \( h_x \) is the equivalent mining height.

4.2 | Main monitoring principles and methods

4.2.1 | Surface deformation monitoring

According to the site geological conditions, the reference, work base, and monitoring points were arranged to regularly and repeatedly determine the spatial position changes of monitoring points on the monitoring line and building during different periods of the mining process. Finally, the monitored data were analyzed for processing.\(^{26}\)

4.2.2 | Index monitoring of vertical feeding system

According to the feeding capacity of the machine, we obtained the mass of vertical feeding in a certain period by calculation.

4.2.3 | Monitoring of underground gangue separation index

Combined with the coal gangue separation capacity required by the mine, according to the coal gangue selectivity and the adaptability of the separation method, the optimal coal gangue separation method is selected. According to the capacity calculation of sorting equipment, the quality of sorting gangue is obtained.
4.2.4 | Monitoring of relevant indexes of working face

(1) Monitoring of dynamic subsidence of roof

The dynamic monitor of the roof was installed vertically in the dense filling body, contacting the roof at the upper part and the bottom at the lower part. The displacement of the roof led to the compression in the measurement part of the monitor. The compression was transformed into an electrical signal. After that, it was uploaded to the detection substation for data analysis.27

(2) Stress monitoring of filling body

Based on strain measurement technology, the backfill stress sensor was used to measure the vertical load stress of coal or rock mass. Under stress action, the deformed filling body transferred the stress to the strain body of the stress sensor to produce lateral deformation. The strain body converted the deformation into a voltage signal, which was then transformed into digital signal output by the transmitter circuit. During installation, the stress sensor of the filling body was fastened to the square steel plate. After cleaning and leveling the floating coal, the steel plate and sensor were fixed at the installation site. Then, the sensor cable was accordingly protected (with pipe or groove steel) and led to the roadway.28,29 The stress layout parameters of the filling body were the same as the setting of the roof dynamic instrument. The backfill stress monitoring was synchronous with roof dynamic monitoring.30

(3) Monitoring of filling mass ratio

According to the principle that the mining volume equals the backfilling volume, the filling mass ratio can be attributed to the density ratio of filling material to coal body. The dynamic filling mass ratio refers to the mass ratio of filling material to mined coal being measured at different time periods by the relevant instrument.

(4) Dynamic compacting ratio

The compacting ratio is the ratio of the final height of the filling body to the mining height under full mining. The dynamic compacting ratio refers to the ratio of the height of the filling body to the mining height after compression at a certain time. Inverse calculations are performed by monitoring the dynamic subsidence of the roof to obtain the dynamic compacting ratio.

5 | CASE ANALYSIS OF ENGINEERING MONITORING IN TANGSHAN MINE

5.1 | Geological conditions of mining

The mining area under the buildings of Tangshan Mine is located in the Tiesan District and the coal pillar district of air shaft industrial square, including Seams 5, 8, 9, and 12 from top to bottom. Five coal seam adopt the general comprehensive mechanized mining and filling mining, and the thickness of T2050 coal seam in the general fully mechanized working face is 2.4 m, the dip angle of the coal seam is 7°, the strike length is 460 m, and the buried depth is 550 m. The filling faces adopted the layout of complete mining and complete backfill of gob, and are divided into working faces F5001, F5001N, F5002, and F5002N. The working face F5001 adopts the mode of upward mining and downward backfilling, with the face length of 63 m, the strike length of 639.5 m, the seam thickness of 2.2 m, and an average incline angle of 11°. In the work, we analyzed the monitoring indexes of F5001.

5.2 | Monitoring program of operating indexes

(1) Monitoring program of vertical feeding index

The normal working hours of the feeding machine are recorded to calculate the index value according to the relevant parameters of the machine.

(2) Monitoring program of gangue separation index

After recording the normal working hours of gangue separation equipment, we calculate the index according to the relevant parameters.

(3) Layout program of rock-pressure monitoring equipment

The monitoring equipment is arranged in the backfilling working face, the filling body, and two roadways. The layout is as follows:

(a) Layout program of backfilling working face monitoring equipment

Backfilling working face monitoring equipment, namely the working resistance monitor of filling hydraulic
support, is used to analyze the roof weighting and periodic breaking law of backfilling working face.

On working face F5001, there are 44 installed hydraulic brackets where 17 working resistance monitors are arranged. The working resistance monitors are on the brackets 3, 4, 5, 8, 10, 14, 17, 20, 22, 23, 25, 26, 28, 32, 35, 38, and 42 (Figure 4).

(b) Layout program of monitoring equipment in filling body of gob

The monitoring equipment for a filling body of goaf consists of the stress monitor of the filling body and the dynamic subsidence monitor of the roof.

In the filling body of the F5001 filling working face, a filling body stress monitor and a roof dynamic subsidence monitor are installed, as shown in Figure 5. According to the previous investigation and traditional rock-pressure experience, the center of gob has the largest roof subsidence and backfill stress. Therefore, the roof subsidence monitor and the stress monitor of the filling body are centrally arranged in the center of the gob. The monitoring equipment is arranged in the middle of the working face F5001 with a length of 66 m.

(c) Layout program of monitoring equipment at two roadways of working face

The monitoring equipment is arranged at two roadways to observe the advanced abutment pressure of the working face. These monitors are arranged before mining and removed when the working face advances to this position. The F5001 filling working face is equipped with measuring stations at 1100 m, 1000 m, 900 m, 800 m, 700 m, 600 m, 500 m, 400 m, and 300 m of the two roadways of the working face. The single hydraulic prop stress monitor is arranged in the station. The layout of the measuring station is shown in Figure 6.

(4) Monitoring program for surface deformation

According to the actual surface conditions of F5001, the general law of mining subsidence, and the topographic characteristics above the working face, we set up a surface observation line F on F5001. A total of 22 measuring points are arranged along Construction South Road and University Road and inside Shizhuang to observe the impact of mining of F5001 on surface subsidence (Figure 7). In the mining process of F5001, the elevation is measured by third-order leveling; the plane displacement is measured by the high-precision measuring robot.

5.3 Actual measurement analysis of implementation effect of “mining, dressing, backfilling, and control” technology

5.3.1 Actual measurement analysis of vertical feeding system indices

(1) Feeding capacity

The monitoring indexes of the automatic control system for backfilling mining material transportation include the total backfilling and ground-feeding gangue mass. Figure 8 shows the monitoring situations of ground-feeding and backfilling mass in Tangshan Mine from July 2016 to July 2017.

It can be seen from Figure 8 that:

During the period from July 2016 to July 2017, the ground input of Tangshan Mine was 9204–40,726 t per month, with an average of 25,936 t. The total filling amount is 9929–47,643 t per month, with an average of 32,494 t and a total of 422,428 t, of which the ground filling amount accounts for 79.82%.
5.3.2 | Actual measurement analysis of gangue separation system indices

(1) Gangue separation capacity

With the integration of mining, dressing, and backfilling, the monitoring index of the underground gangue separation system is underground separated gangue. During the period from July 2016 to July 2017, the underground sorting amount was 85,257 t. The average monthly sorting gangue quality is 6558 t, up to 12,962 t.

The ground-feeding capacity is integrated with the underground coal gangue separation capacity. Under the same backfill conditions, the totally filled mass can reflect the effect of “control.”

5.3.3 | Actual measurement analysis of the indices of the backfilling mining system

(1) Support effect

The monitoring indices of the working-face rock-pressure-monitoring system are periodic weighting steps and dynamic factors. When F5001 advances 430 m, we obtain the changes of the above indices from October 10 to December 31, 2016 (Figures 9 and 10).

Figures 9 and 10 show that the average periodic weighting step of F5001 is 30.14 m, and the dynamic factor does not change much during this process, with an average value of 1.12. According to the changes in the working resistance and dynamic factor of weighting support, the
backfilling mining of the working face has effectively controlled strata behaviors of the stope.

(2) **Advance abutment pressure**

The pressure of a single pillar is monitored by the advanced pressure monitor, deriving the comparative relationship between the advanced abutment pressure and the advancement of working faces F5001 and T2050. The measuring station is 140 m away from the open-off cutting, being arranged on a single pillar in return airflow roadway of the working face. The monitoring starts when the working face advances 100 m and ends when it arrives at the measuring station (Figure 11).

Figure 11 shows that the advance stress range of F5001 is 2–3 MPa; the advance stress affected zone is 13.7 m; the stress concentration factor is 1.26. The measured law of advance stress of the caving face T2050 is similar to the filling law, with a stress concentration coefficient of 1.84.

According to the reduction in advanced abutment pressure and influence range, the stope pressure has effectively controlled to a certain extent.

(3) **Backfill deformation and dynamic compacting ratio**

The peak stress is 6.12 MPa, which exceeds 104% of F5001; the advanced influence distance is 23.7 m, which exceeds 73% of F5001.

According to the reduction in advanced abutment pressure and influence range, the stope pressure has effectively controlled to a certain extent.
In Tangshan Mine, the dynamic sinker of the roof of F5001 is located in the middle of the working face which is 245 m away from the open-off cutting. From May 18 to June 28, 2017, the working face advances 150 m. The advanced roof subsidence is 238 mm before backfilling, and the total backfill deformation is 211.5 mm after backfilling (Figure 12). The backfill deformation can be divided into four stages:

(a) More rapid deformation stage I (0–13.9 m)

Stage I is 245–258.9 m away from the open-off cutting. At Stage I, the backfill deformation is 110.4 mm; the roof subsidence is 348.4 mm; the average deformation rate is 8.17 mm/m; the dynamic compacting ratio drops to 86.3%. The filling body has a large deformation rate at this stage because of the loose structure and large porosity.

(b) Rapid deformation stage II (13.9–69.3 m)

Stage II is 258.9–314.3 m away from the open-off cutting. At Stage II, the backfill deformation is 84.9 mm; the roof subsidence is 433.3 mm; the average deformation rate is 1.52 mm/m; the dynamic compacting ratio drops to 81.7%. The backfill deformation rate slows down. At this stage, the bearing capacity of the filling body gradually increases to slow down the deformation rate. However, the overall deformation remains large.

(c) Slow deformation stage III (69.3–136.1 m)

Stage III is 314.3–381.1 m away from the open-off cutting. At Stage III, the backfill deformation is 24 mm; the roof subsidence is 457.3 mm; the average deformation rate is 0.36 mm/m; the dynamic compacting ratio drops to 81.2%. At this stage, the filling body is gradually compacted. Besides, the backfill deformation and roof migration tend to be stable.

(d) Stable creep stage IV (136.1–150 m)

Stage IV is 381.1–395 m away from the open-off cutting. At Stage IV, there is no backfill or roof deformation. The maximum backfill deformation stabilizes at 211.5 mm; the dynamic compacting ratio is at 81.3%. The roof has entered a stable creep stage.

According to the above four stages, with the continuous advancement of the working face, the deformation and subsidence rate of the filling body is getting smaller and smaller. The roof deformation is positively correlated with the deformation of the filling body and negatively correlated with the filling rate.

(4) Backfill stress and secant modulus

In Tangshan Mine, the backfill stress sensor of F5001 is located in the middle of the working face which is 245 m away from the open-off cutting. From May 18 to June 28, 2017, the working face advances 150 m; the backfill stress rises from 0.2 to 2.78 MPa. Figure 13 shows the change law of backfill stress with advance distance in F5001 of Tangshan Mine.

It can be seen from Figure 13 that the stress of the filling body increases with the advancement of the working face.
face; when the working face is 94 m away from the stress sensor, the stress of the filling body tends to be stable, and the stable value is 2.78 MPa.

The secant modulus is calculated by the ratio of the filling body stress to its strain. In the process of working face advancing, the filling body is gradually compacted, and the stress and deformation of the filling body tend to be stable. When the filling body is fully compacted, the secant modulus will become a constant value; the stability value of the secant modulus of the filling body is 32 MPa through calculation.

(5) Filling mass ratio

During the mining process of the F5001 working face, we monitored the filling mass ratio from July 2016 to December 2016. The monthly filling mass ratio is shown in Figure 14.

Figure 14 shows that the filling mass ratio of F5001 stabilizes around 1.28, ranging from 1.16 to 1.5. The greater filling mass ratio leads to the greater compacting ratio. The compacting ratio is a comprehensive index reflected by the backfill deformation, compression, and filling ratios.

5.3.4 Actual measurement analysis of ground deformation indices

The observation of surface movement and deformation began in November 2016, and a total of 15 observations were made up to April 2018. A measuring line was arranged, where the accuracy met the requirements of the Coal Mine Survey Regulations. The measuring points are arranged above the F5001 working face, from F1 to F22, a total of 22 points; F6, F9 point in the middle of the F5001 working face, this section analysis only based on F6, F9 two measuring points, other measuring points analysis are similar.

Figure 15 shows that the subsidence values of F6 and F9 points show an upward trend from December 2016 to March 2018, and the upward trend of F6 points is the most obvious. The maximum subsidence values at F6 and F9 in January 2018 were 49 mm and 32 mm, respectively. The deformation value meets the fortification standard of the 2017 Regulations for Retention of Coal Pillars and Mining of Compressed Coals in Buildings, Water Bodies, Railways, and Main Shafts. There is a functional relationship between the surface subsidence value and other surface subsidence indexes. Through the monitoring of surface subsidence, other deformation parameters can be solved, and the effect of surface control can be fully reflected by combining the size of the index.

6 | MONITORING EVALUATION AND RECOMMENDATIONS

6.1 Overall evaluation of measured indices

The analysis of monitoring indices showed that the actual capacities of feeding, gangue separation, and backfilling systems were 337,171, 85,257, and 422,428 t/year, respectively. The filling mass ratio was 1.28; the stress concentration factor was about 1.26; the average periodic weighting step was 30.14 m; the average dynamic factor variation was 1.12. Small stress concentration and dynamic factors indicated that backfill mining could effectively reduce the strength of strata behaviors. The compacting ratio of the working face reached 82%; the maximum surface subsidence was 49 mm; the secant modulus of the filling body was stable at 32 MPa; the backfill stress stabilizes at 2.78 MPa. These indices met the requirements of preventing the destruction of surface structures.

6.2 Recommendations for the implementation of “mining, dressing, backfilling, and control” technology

The implementation of backfilling mining technology for the gangue not raising the well can effectively control surface subsidence, hard roof, and stope pressure. Coal mining enterprises can adjust system operation monitoring, equipment selection, backfill materials, intelligent control of feeding, and separation systems to ensure the effectiveness of technology implementation. The system operation reliability and data accuracy must be improved for better system monitoring. The safety and reliability of equipment operation are ensured for better equipment selection under the premise of economic rationality. In addition, the ratio and strength of backfill materials should be comprehensively integrated. Economically, the higher strength of backfill materials leads to a better compacting
ratio and control effect. For the intelligent control of feeding and separation systems, it is necessary to improve the stability of equipment and system operation. Generally, there are various methods to ensure the implementation effect of the “mining, dressing, backfilling, and control” technology. From the perspective of safety and efficiency, the systems are fully integrated into operation to achieve the optimal control effect.

7 | CONCLUSIONS

1. The work introduced the principle, operating characteristics, and integrated backfilling process of the “mining, dressing, backfilling, and control” technology. After that, the monitoring method was proposed for integrated operation indices, thus establishing the index monitoring system.

2. The measured indices of Tangshan Mine included vertical feeding, gangue separation capacity, advanced abutment pressure, backfill subsidence, stress, compacting ratio, filling mass ratio, and surface deformation. After analysis, we obtained the index change rules of ground solid waste treatment, transportation, vertical feeding, underground gangue separation, and fully mechanized mining backfilling systems.

3. Taking Tangshan Mine as an example, the parameters of monitoring indices were adjusted according to the conditions of overlying strata and working face between mines, thus optimally reflecting the “control” effect.

4. Research results provided evidence for theoretical and technical research deepening of “mining, dressing, backfilling, and control” technology, and technical references for mines with similar geological conditions and engineering problems.

ACKNOWLEDGMENTS

The work was supported by the National Natural Science Foundation of China (52174134), the National Natural Science Foundation of China (51904110), and the Fundamental Research Funds for the Central Universities (2021GJZPY12). The authors gratefully acknowledge the financial support from these organizations.

CONFLICT OF INTEREST

None.

ORCID

Zhang Qiang  https://orcid.org/0000-0003-0770-7407

REFERENCES

1. Mixo X, Qian M. Research on green mining of coal resources in China: current status and future prospects. J Min Saf Eng. 2009;26(1):1-14.

2. Wu X, Zhang S. The formation of the concept of green development and future trend. Econ Iss. 2017;2:30-34.

3. Liu J, Xie H, Wang J, et al. Study on disruptive technology development counter measure of coal green development and utilization. Coal Econ Res. 2017;37(12):6-10.

4. Sun X. Present situation and prospect of green backfill mining in mines. Coal Sci Technol. 2020;48(09):48-55.

5. Zhang J, Zhang Q, Ju F, et al. Theory and technique of greening mining integrating mining, separating and backfilling in deep coal resources. J Chin Coal Soc. 2018;43(02):377-389.

6. Hu B, Liu P, Cui F, et al. Review and development status of backfill coal mining technology in China. Coal Sci Technol. 2020;48(09):39-47.

7. Hao D, Bai Q, Li W, et al. Mining technology of “mining, dressing, backfilling and drainage” with less gangue in deep high gas mine protective layer. J Min Saf Eng. 2020;37(01):93-100.

8. Zhang P, Zhang Y, Zhao T, et al. Ground control monitoring in backfilled strip mining under the metropolitan district: case study. Int J Geomech. 2018;18(7):102.

9. Zhang Q, Zhang J, Kang T, Sun Q, Li W. Mining pressure monitoring and analysis in fully mechanized backfilling coal mining.

FIGURE 14 Actual measurement law of the filling mass ratio

FIGURE 15 Sinking law of F6 and F9 measuring points
face - a case study in Zhai Zhen Coal Mine. J Central South Univ. 2015;22(05):1965-1972.

10. Tang K. Research on mining subsidence monitoring in mining area based on standalone CORS. Geomat Spat Inform Technol. 2017;40(1):162-164.

11. Zhang J, Zhang Q, Ju F, et al. Practice and technique of green mining with integration of mining, dressing, backfilling and X in coal resources. J Chin Coal Soc. 2019;44(1):64-73.

12. Ju F. Development and engineering applications of solid materials vertical transportation system in backfill coal mining technology. Xu Zhou: China Univ Min Technol. 2012;67-90 (in Chinese).

13. Ju F, Zhang J, Wu Q, et al. Vertical feeding & transportation safety control technology for solid backfill materials in coal mine. Disaster Adv. 2013;6(S5):154-162.

14. Ju F, Zhang J, Zhang Q. Vertical transportation system of solid material for backfilling coal mining technology. Int J Min Sci Technol. 2012;22(1):41-45.

15. Zhang H, Zhang Q, Zuo X, et al. Design and application of mining-separating-backfilling system for mining ecological and environmental protection. J Chin Univ Min Technol. 2021;50(03):548-557.

16. Zhang J, Ju F, Li M, et al. Method of coal gangue separation and coordinated in-situ backfill mining. J Chin Coal Soc. 2020;45(1):131-140.

17. Tu S, Hao D, Li W, et al. Construction of the theory and technology system of selective mining in “mining, dressing, backfilling and X” integrated mine. J Min Saf Eng. 2020;37(01):81-92.

18. Zhang Q, Zhang J, Zhao X, Liu Z, Huang Y. Industrial tests of waste rock direct backfilling underground in fully mechanized coal mining face. Environ Eng Manage J. 2014;13(5):1291-1297.

19. Li M. Mechanical Behavior of Gangue Backfill Material and Control Mechanism of Strata Movement. China University of Mining and Technology; 2018.

20. Zhang Q, Zhang J, Ju F, et al. Backfill body’s compression ratio design and control theory research in solid backfill coal mining. J Chin Coal Soc. 2014;39(01):64-71.

21. Zhang Q, Zhang J, Wang J, et al. Theoretical research and its engineering practice on critical backfill ratio in backfill mining. J Chin Coal Soc. 2017;42(12):3081-3088.

22. Yan H, Zhang J, Ju Y, et al. Fracture development rules controlled by backfill body’s compression ratio and gas drainage technology under upper protective layer mining. J Min Saf Eng. 2018;35(06):1262-1268.

23. Zhou Y, Chen Y, Zhang J, et al. Control principle and technology of final compression ratio of backfilling materials. J Min Saf Eng. 2012;29(03):351-356.

24. Zhang Q, Zhang J, Han X, Ju F, Tai Y, Li M. Theoretical research on mass ratio in solid backfill coal mining. Environ Earth Sci. 2016;75(7):586.

25. Zhang J, Zhang Q, Sun Q, Gao R, Germain D, Abro S. Surface subsidence control theory and application to backfill coal mining technology. Environ Earth Sci. 2015;74(2):1439-1448.

26. Wang D, Huang H. Research and system design of surface subsidence deformation monitoring technology. Beijing Survey Map. 2016;06:41-44+59.

27. Geng Q, Yao S, Zhang P, et al. Overlying strata deformation monitoring of backfill mining and influential factors of control effect analysis. China Coal. 2018;44(01):46-49.

28. Zhao T, Zhang Y, Zhang Z, Li Z, Ma S. Deformation monitoring of waste rock backfilled mining gob for ground control. Sensors (Basel, Switzerland). 2017;17(5):1044.

29. Zhao T, Ma S, Zhang Z. Ground control monitoring in backfilled strip mining under the metropolitan district: case study. Int J Geomech. 2018;18(7):05018003.

30. Zhang Q, Zhang J, Huang Y, Ju F. Backfilling technology and strata behaviors in fully mechanized coal mining working face. Int J Min Sci Technol. 2012;22(2):151-157.

How to cite this article: Qiang Z, Yang K, Zhang J, et al. Monitoring and measurement analysis of key indexes for the implementation of mining, dressing, backfilling, and controlling technology in coal resources—A case study of Tangshan Mine. Energy Sci Eng. 2022;10:680–693. doi:10.1002/ese3.1057