Research Article

Calculation of Subsidence due to Longwall Mining with Overburden Grouting and Its Application

Hewen Ma,1,2,3,4 Yadong Ji,1,2 and Shidong Wang1,2

1Xi’an Research Institute Co., Ltd., China Coal Technology & Engineering Group Corp., Xi’an, 710077 Shaanxi, China
2Key Laboratory of Coal Mine Water Hazard Prevention and Control Technology in Shaanxi Province, Xi’an, 710077 Shaanxi, China
3Huaibei Mining Group Co. Ltd., Huaibei, 235000 Anhui, China
4School of Resources and Geosciences, China University of Mining and Technology, Xuzhou, 221008 Jiangsu, China

Correspondence should be addressed to Hewen Ma; mahewen@cctegxian.com
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This paper presents a prediction method of mining-induced surface subsidence due to longwall mining with overburden grouting, which has been proven an effective method to mitigate the overburden failure. This paper proposes a partial overburden grouting (POG) mining method based on surface subsidence basin inversion and innovative longwall panel layout to mitigate overburden failure and subsidence. A prediction model of surface subsidence with overburden grouting, namely, overburden grouting equivalent calculation model (OGECM), is proposed. In this study, an engineering design process and method of POG was established, the strike and dip excavation length and grouting quantity combined as critical indicators for determining the key parameter in surface basin control. In applications at the field grouting test, the surface subsidence characteristics of POG on the side of the opening line of longwall panel were investigated through surface observation station and estimated surface subsidence reduction ratio based on OGECM with grouting compared with those without. The field measurement validated the new subsidence calculation method. POG technology applied to subsidence control has effectiveness in controlling the surface subsidence to less engineering cost but expanding the applications.

1. Introduction

Surface subsidence may occur when the subsurface coal is excavated induced the nonequilibrium of the original internal stress to lead to rock strata bending and broken in disturbed overburden [1–4]. The surface subsidence is one of the most common disasters and may cause farmlands destruction, ground buildings damages and water logging [5–8]. Over the past decades, with coal excavation increased, the social and environmental problem associated mining subsidence in China has become progressively more serious [9–12] and induced the development of measures to mitigate surface subsidence and improve surface environment, such as strip coal pillar mining, backfilling method, overburden grouting [13–16], and soil reinforcing [17–19]. Overburden grouting method as one of the special mining method is considered to be an effective method to mitigate overburden failure and control surface subsidence without affecting the subsurface mining [20–22].

Overburden grouting, as one of surface subsidence control technology, involves the fly ash slurry injected into bed separation space by the high pressure pumping to control surface subsidence induced by coal excavation [23]. Compared with backfilling method, it interferes little with subsurface coal excavation due to grout injection into overburden. In recent years, application of overburden grouting technology has increased in Australia and China [24–26]. The field investigation of overlying strata movements and stress concentration shows the subsidence reduction ratio (which is the ratio of surface subsidence reduction to surface subsidence without grouting) close to 50% at West Cliff Colliery. Overburden grouting has been implemented for more than 30 years in China; subsidence reduction ratio can reach 36%-65% in some
coal mines, such as Fushun, Xinwen, Huaibei, and Huainan. Improved overburden grouting technique based on adjusting chain pillar and selecting the grouting position among adjacent panels can obtain a better subsidence control effect. When multiple panels are excavated, the first longwall panel implementing overburden grouting achieves the best effect of reducing surface subsidence [20]. Dividing the longwall panel in grouting area combining with coal pillars and grouting body to control surface subsidence can improve the subsidence reduction ratio and overlying strata stability [27]. The boundaries of injection body locate above the edges of longwall gob, and a supporting area is formed at the center of gob under the overburden grouting. The surface subsidence can be estimated based on the injected fill distribution model, which facilitates injection design and evaluation of subsidence control effectiveness [22, 28]. Considering the factors of excavation and geology, the distance of grouting strata from coal seam and grouting time can establish a time function model to predict the dynamic subsidence during overburden grouting with a uniform grout injection rate [29]. Scanning electron microscopy, scale model test, and fractal theory can be used to study grouting slurry, fracture of strata to optimize grouting technology [30–33].

Grouting injection, remaining coal pillars, and increasing the width of panel can enhance the surface subsidence reduction ratio. Those previous improved technologies increase overburden stability and reduce residual subsidence. These methods will lead to unrecoverable coal increasing. However, coal production decreases in line with increase in unrecoverable coal to some extent. Combining traditional subsidence prediction method (probability integral method) and grouting body distribution model together predicts surface subsidence during overburden grouting, subsidence reduction ratio is proportional to injection-production ratio (which is the ratio of injection quantity to excavated coal quantity). The previous research on predicted model and formula are applicable to bed separation developed under strong strata based on overburden grouting or suit for regional coalfield, which are not universally suitable for surface subsidence prediction of overburden grouting [22, 34]. This paper proposes a partial overburden grouting mining method (POG) to control the surface movement and deformation to protect buildings and infrastructures based on a relatively new panel layout design method. The panel layout is designed based on the maximum security standard from strike and dip direction. The width and length of excavation and grouting injection volume are key parameters in POG technology. Moreover, a new prediction model is proposed. On the premise of ensuring the ground constructions undamaged, optimizing production efficiency and saving engineering cost should be considered in POG technology. In this study, the POG mining method was discussed and applied in field testing.

2. Methodology

2.1. Panel Layout Design Principle. The principle of longwall panel layout design referring to implementing overburden grouting is established on the basis of surface subsidence reduction requirement and injection-production ratio. The POG technology refers to limiting both width and length of longwall panel in subcritical mining condition to meet the requirement of surface subsidence reduction and achieve the optimal configuration of grouting quantity and coal production. With the width of panel reduced, excavation scale, overburden failure, and surface subsidence are mitigated correspondingly. The panel layout design method is based on pre-extraction estimated of subsidence and reaches the following requirements: (1) Surface subsidence and deformation must be controlled to meet security criteria of ground constructions after coal mining and (2) Area of width shortened of longwall panel should be as small as possible to reduce the coal pillars size and unrecoverable coal.

2.2. Surface Movement and Deformation Prediction. Surface subsidence reduction ratio is affected by longwall panel dimension with the same grouting quantity and mining height. Limiting the width of panel to a subcritical size can mitigate the surface subsidence. The more the area of longwall panel is, the more surface subsidence is. The more distance from the surface subsidence basin is, the smaller surface deformation is.

Figure 1 shows three types of surface subsidence basin, subcritical subsidence basin, critical subsidence basin, and supercritical subsidence basin. When the width of panel is more than double radius of major influence \( (s > 2r) \), surface deformation is supercritical subsidence basin; when the width of panel is equal to double radius of major influence \( (s = 2r) \), surface deformation is critical subsidence basin; when the width of panel is less than double radius of major influence \( (s < 2r) \), surface deformation is subcritical subsidence basin. The area of surface subsidence basin is much larger than the excavation area. Furthermore, the strike and dip length of longwall panel will affect deformation degree of surface subsidence basin. And different positions in surface subsidence basin have the different degrees of surface movement and deformation.

Through the above analysis, the maximum permissible deformation for ground constructions is determined by the deformation of the different positions in surface subsidence basin. The permissible surface deformation guides panel layout design and application of the POG technology in surface subsidence control. Furthermore, it can be used as a crucial index to predict surface subsidence reduction ratio and injection-production ratio.

The prediction of surface subsidence and subsidence reduction ratio is an essential procedure before overburden grouting to control surface subsidence. The probability integral method was developed based on the stochastic medium theory proposed by Litwiniszyn [35, 36]. And it is the most widely applied in surface subsidence prediction. The inhomogeneous deformation and fissures in the rock mass occurred due to coal excavation. The volume of goaf will not disappear without reasons based on macro analysis, which will transmit inside the rock mass, that is, distributed in the internal fissures of the overburden above the goaf and the surface subsidence basin. It relates overburden deformation to surface subsidence due to coal excavation. The surface deformation and overburden movement induced by coal excavation can be considered an isotropic medium and a random process, which obeys statistical regularity. Statistically, the entire longwall panel
can be divided into an infinite number of infinitesimal units, and surface movement or deformation of the entire longwall panel is equal to the sum of that induced in the all infinite number of units. Therefore, the deformation of surface subsidence basin conforms to normal distribution, and its profile can be represented by the integral equation of a probability density function. The State Administration of Work Safety [37] recommended the generalized predicting formula for surface subsidence on the basis of the probability integral method:

\[ W(x) = \frac{mh \cos \alpha}{2} \left[ \text{erf} \left( \frac{\sqrt{\pi x}}{x'} \right) + 1 \right], \]  

\[ i(x) = \frac{m \eta \cos \alpha}{r} e^{-\pi x^2/r^2}, \]  

\[ K(x) = -2\pi \frac{m \eta \cos \alpha}{r^3} xe^{-\pi x^2/r^2}, \]  

\[ e(x) = -2\pi b \frac{m \eta \cos \alpha}{r^2} xe^{-\pi x^2/r^2}, \]  

\[ u(x) = b n \eta \cos \alpha e^{-\pi x^2/r^2}, \]  

where \( m \) is the excavation height of coal seam; \( \eta \) is the subsidence factor; \( \alpha \) is the dip angle of coal seam; \( x \) is the calculation point; \( r \) is the main influencing radius, \( r = H / \tan \beta \); \( e \) is a mathematical constant; \( b \) is the horizontal movement constant; \( H \) is the mining depth; \( \tan \beta \) is the tangent of the main angle of influence; \( W(x) \) is the surface subsidence value; \( i(x) \) is the slope value; \( K(x) \) is the curvature deformation; \( e(x) \) is the horizontal deformation; and \( u(x) \) is the horizontal migration.

The bed separation is regarded as the deformation and subsidence inside the overburden; the bed separation can be similar to the subsidence basin inside overlying strata. During the coal excavation, bed separation as an internal unit moves relatively in the overlying strata. Thus, the main influencing radius and the horizontal movement constant of the bed separation can be expressed as

\[ r(x') = \frac{H - x'}{\tan \beta(x')}, \]  

\[ b(x') = b \left( \frac{H - x'}{H} \right)^{n-1}. \]  

where \( x' \) is the calculation point of the bed separation; \( H \) is the mining depth; \( b \) is the horizontal movement constant; \( r(x') \) is the linear function, which is the main influencing radius inside the overburden; \( b(x') \) is the horizontal movement constant inside the overburden; and \( \tan \beta(x') \) is the constant expressed as follows:

\[ \tan \beta(x') = \left( \frac{H - x'}{H} \right)^{n-1} \tan \beta, \]  

where \( \tan \beta \) is the tangent of the main angle of influence and \( n \) is the index of the main influencing radius related to the mechanical properties of rock, which can be expressed as

\[ n = -2\pi H^{-1} b \tan \beta. \]  

The difference between the surface subsidence and the subsidence model inside overlying strata is the main influencing radius. By substituting Equation (6), Equation (7), and Equation (8) into Equation (10) and Equation (11), the vertical displacement and the horizontal displacement of subsidence model inside overlying strata can be determined as

\[ hb = \frac{m \eta \cos \alpha}{2} \left[ \text{erf} \left( \frac{\sqrt{\pi x}}{x'} \right) + 1 \right], \]
\[ L_b = b \left( x' \right) \eta \cos \alpha e^{-\pi x'^2 / r^2(x')} \]  

(11)

where \( h_b \) is the height of different point of bed separation and \( L_b \) is the horizontal displacement of bed separation.

Assuming that the bed separation space is distributed evenly, the actual thickness of filling body inside bed separation is less than the height of bed separation space developed because the bed separation space cannot be filled completely. Thus, the injection-production ratio is always less than 1. The actual thickness of filling body is affected by injection-production ratio, then

\[ h_i = h_b \times a, \]  

(12)

\[
\begin{align*}
W(x') &= \frac{h_i h \cos a}{2} \left[ \text{erf} \left( \frac{\sqrt{\pi x'}}{r(x')} \right) + 1 \right] \\
n(x') &= \frac{h_i h \cos a}{r(x')} e^{-\pi x'^2 / r^2(x')} \\
K(x') &= -2 \pi \frac{h_i h \cos a}{r(x')} x' e^{-\pi x'^2 / r^2(x')} , L_b \geq 2r(x') , \\
\xi(x') &= -2 \pi b(x') \frac{h_i h \cos a}{r(x')} x' e^{-\pi x'^2 / r^2(x')} \\
u(x') &= b(x') h_i h \cos a \cdot e^{-\pi x'^2 / r^2(x')} 
\end{align*}
\]

(13)

where \( l \) is the calculating width of bed separation, \( l = L_b - 2d \) (\( d \) is the offset of the inflection point); \( W(x') \) is the surface subsidence reduction under overburden grouting; \( n(x') \) is the slope reduction under overburden grouting; \( K(x') \) is the curvature deformation reduction under overburden grouting; \( \xi(x') \) is the horizontal deformation reduction under overburden grouting; and \( u(x') \) is the horizontal migration reduction under overburden grouting.

The overburden grouting calculation mining model is substituted surface subsidence reduction under overburden grouting directly due to the residual bulking factor of caved rocks considered in the above formulas. The surface
subsidence prediction based on overburden grouting can be determined as

\[
\begin{align*}
W'(x) &= W(x) - W(x) \\
i'(x) &= i(x) - i(x) \\
K'(x) &= K(x) - K(x) \\
\varepsilon'(x) &= \varepsilon(x) - \varepsilon(x) \\
u'(x) &= u(x) - u(x)
\end{align*}
\]

\[\text{(15)}\]

2.3. POG Technique

2.3.1. Principle. Partial overburden grouting (POG) technology, differing from previous overburden grouting technique, meets requirements of surface subsidence control based on overburden grouting for the purpose of panel layout design reasonably (Figure 3). The requirement of surface subsidence reduction depends on the maximum permissible deformation for ground protective constructions. POG technology involves overburden grouting and longwall panel layout on the basis of permissible deformation inversion and prediction of subsidence reduction and grouting quantity (Figure 4). First, surface subsidence and deformation are predicted without grouting based on the geological and mining condition. Furthermore, the maximum permissible surface movement and deformation is as the security criteria to determine surface subsidence reduction inversion. These are the key indicators to guide panel layout design and overburden grouting on the basis of the optimality theory. Finally, according to actual engineering, panel layout is reasonably adjusted, and surface observation station is established to monitor the surface deformation (Figure 5).

2.3.2. Prediction of Overburden Grouting Quantity. The reasonable grouting quantity has a significance to reduce the difficult of overburden grouting and guide the implementation to achieve subsidence reduction ratio. The estimation of grouting quantity is determined by the subsidence reduction and injection-production ratio. The final existence form of slurry injected is the saturated fly ash aggregate on the compacted condition, which plays a direct role in supporting overlying strata and controlling surface subsidence. Moreover, some water solidifies with cement or other coagulants of the injected
slurry, and the excessive water of injected slurry will gradually flow away along terrane fractures with seepage. Therefore, the key role of supporting overlying strata and reducing surface subsidence is not the slurry injected but the compacted fly ash aggregate. Thus, the saturated solid volume of slurry is equivalent of the dry fly ash volume. And the saturated solid volume can be calculated through the injected slurry quantity referring to water-cement ratio. Then, the mined-out coal volume \( V \) in the overburden grouting area is as the follows:

\[
V = CDLm,
\]

where \( C \) is coal recovery ratio; \( D \) is the strike length of panel; \( L \) is the dip length of panel; and \( m \) is the excavation height of coal seam.
The volume of dry fly ash injected is obtained as follows:

\[ V_g = aCDLm, \]  

where the \( V_g \) is the injected fly ash volume and \( a \) is the injection-production ratio.

2.3.3. Overburden Grouting Quantity Distribution Vs Excavation. In order to achieve a better effect of surface subsidence control and the fly ash injected occupying a certain space in bed separation, it is necessary to ensure the relationship between grouting quantity and coal production per unit time. And it can be express as follows:

\[ V_d = aCDL_d m, \]  

where \( D_d \) is the excavation length of longwall panel in strike direction per unit time and \( L_d \) is the excavation length of longwall panel in dip direction per unit time.

2.4. Field Grouting Test and Measurements

2.4.1. Site Description and Geological Mining Conditions. The study site is selected where there are 3 villages linked together in ground surface above panel. Longwall panel No.366, the focus of this paper, is a typical case where a protective area spanning 78 m above the open-off cut of longwall panel. The ground surface terrain is flat. The coal seam is nearly horizontal which overlying strata is medium-hard rock and the average thickness of bedrock is 187 m. The average buried depth is 480 m. The panel is fully mechanized caving panel with 187 m width of panel in original design, and the mining height is 4 m.

2.4.2. Engineering Design for Panel Layout Based on Overburden Grouting. In order to guarantee the safety of ground constructions located in the coal mining area, the State Administration of Work Safety identifies the levels of constructions damage (Table 1). In this paper, the main constructions in the protective village area are rural houses, and the allowable structure deformations are in the first level damage.

3. Results and Analysis

3.1. Purpose of Surface Subsidence Controlling. The probability integral method is a common method to predict the surface subsidence and deformation and guide the engineering application in protective constructions area. The predictive parameters of surface subsidence are selected with reference to the surface movement and deformation data obtained from the Tongting Coal Mine and the Linhuan Coal Mine with similar mining conditions near the No.366 panel as follows: the mining height of coal seam (m) is 4 m; the subsidence factor (\( \eta \)) is 1.0; the tangent of the main angle of influence (\( \tan \beta \)) is 1.8; and the horizontal movement constant (\( \xi \)) is 0.32. The 187 m width of original panel design is selected as the predictive index to predict surface subsidence.

Without overburden grouting, the prediction value of the maximum subsidence, slope, curvature, horizontal displacement, and horizontal deformation in surface subsidence basin reaches 2100 mm, 10 mm/m, 0.14 mm/m², 1000 mm, and -11 ~ +5 mm/m, respectively (Table 2). The prediction value of the maximum subsidence, slope, curvature, horizontal displacement, and horizontal deformation in protective villages area reaches 1600 mm, 8 mm/m, 0.08 mm/m², 600 mm, and -9 ~ 3 mm/m, respectively. Referring to the Chinese classification table of critical deformation values of surface concrete structures (Table 1), it is concluded that some of ground buildings have been damaged in grade four and need to be overhauled or demolished after coal mining in study site. Referring to parameters of Table 1, the aim of villages’ protection is in level I. Thus, the subsidence reduction ratio is determined to guide grouting quantity and panel layout design reasonably based on the prediction values of the maximum movement and deformation inversion in protective village area.

3.2. POG Technology Design for Overburden Grouting

3.2.1. Panel Layout Optimization. The surface deformation and bed separation space developed are determined by longwall panel size. With the same coal recovery ratio, different mining sizes will cause different degrees of surface subsidence. The width of longwall panel will intensify the surface movement and deformation [30]. Thus, the panel width is less than 150 m due to 152~222 m of the range of bedrock thickness. Surface subsidence caused in different panel width is predicted, as shown in Figure 6.

When the panel width is 120 m, the maximum subsidence is 1.58 m; when the panel width is 130 m, the maximum subsidence is 1.73 m. The requirement of surface subsidence reduction ratio would increase with the panel width increased, which needs the higher surface subsidence reduction ratio. With the 0.5 of surface subsidence reduction ratio predicting, the maximum surface subsidence is less than 0.5 m. Moreover, according to the ground protective constructions locating position of surface subsidence basin, the subsidence of protection villages is 1.47 m and 1.55 m on the condition of 120 m and 130 m of the panel width, respectively. Figure 6 shows that the reasonable panel width is in range of 120~130 m to meet the surface subsidence reduction ratio. Thus, the requirement of surface subsidence reduction ratio for overburden grouting is in a range of 0.66~0.68 in protection villages. Furthermore, the panel width should be the 127 m due to the efficient full-mechanized mining.

The shorten area of longwall panel should be the smaller the better to mitigate the impact on coal production. Figure 7 shows the relationship between the dip length and the strike length of longwall panel. On the basis of the panel width determined, the strike length can be divided into the length of shorten-width area (L1) and the full-width area (L2). With the different combinations of length of L1 and L2, the subsidence prediction of protection villages are shown in Table 3. It shows that the values of subsidence, slope, and horizontal strain are no longer changing significantly on the condition of the \( L1 > 350 \) m. When the length of \( L1 \) is in a range of 200~300 m, the constructions in protection villages will suffer level I damage, and the value of horizontal strain is still large. Therefore, the strike length of shorten-width panel is 350 m.
Table 1: Classification of critical deformation values of surface concrete structures [37].

<table>
<thead>
<tr>
<th>Damage level</th>
<th>Horizontal strain (mm·m⁻¹)</th>
<th>Slope (mm·m⁻¹)</th>
<th>Curvature (mm·m⁻²)</th>
<th>Classification</th>
<th>Structural processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>≤2.0</td>
<td>≤3.0</td>
<td>≤0.2</td>
<td>Negligible damage</td>
<td>No repair</td>
</tr>
<tr>
<td>II</td>
<td>≤4.0</td>
<td>≤6.0</td>
<td>≤0.4</td>
<td>Slight damage</td>
<td>Light repair</td>
</tr>
<tr>
<td>III</td>
<td>≤6.0</td>
<td>≤10.0</td>
<td>≤0.6</td>
<td>Medium damage</td>
<td>Medium repair</td>
</tr>
<tr>
<td>IV</td>
<td>&gt;6.0</td>
<td>&gt;10.0</td>
<td>&gt;0.6</td>
<td>Severe damage</td>
<td>Heavy repair or reconstruction</td>
</tr>
</tbody>
</table>

Table 2: Ground and villages deformation prediction without grouting.

<table>
<thead>
<tr>
<th>Mining directly</th>
<th>Subsidence (mm)</th>
<th>Slope (mm·m⁻¹)</th>
<th>Horizontal strain (mm·m⁻¹)</th>
<th>Curvature (mm·m⁻²)</th>
<th>Horizontal displacement (mm)</th>
<th>Damage level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>-2100</td>
<td>10</td>
<td>-11–5</td>
<td>-0.14</td>
<td>1000</td>
<td>IV</td>
</tr>
<tr>
<td>Villages</td>
<td>-1600</td>
<td>8</td>
<td>-9–3</td>
<td>0.08</td>
<td>600</td>
<td>IV</td>
</tr>
</tbody>
</table>

Figure 6: The surface subsidence prediction for different panel widths (without grouting).
3.2.2. Grouting Injection Quantity Prediction. According to Formulas (16) and (17), the estimated parameters of the subsidence reduction ratio required and the injection-production ratio ($a$) are 0.75 and 0.3, respectively. The goaf volume is equal to the sum volumes of shorten-width panel and the full-width panel. The goaf volume of shorten-width panel and the full-width panel is about 184,072 m$^3$ and 116,158 m$^3$, respectively. Based on 0.3 of the injection-production ratio, the sum of predictive volume of injected fly ash is about 90,069 t ones.

The overburden grouting is in normal operation in matching mining speed with grouting speed to ensure that the injected fly ash can occupy a certain space in bed separation. The reasonable mining speed is determined so as to ensure the engineering proceeding smoothly based on the maximum grouting quantity per unit time achieved in actual grouting station. Based on the minimum injection-production ratio (0.3), the mining speed can be predicted by Equation (18) in the different width of panel. Figure 8 shows the grouting

![Table 3: Villages subsidence prediction for the different mining schemes with grouting.](image)

<table>
<thead>
<tr>
<th>Scheme</th>
<th>$L_1$ (m)</th>
<th>$L_2$ (m)</th>
<th>Subsidence (mm)</th>
<th>Slope (mm·m$^{-1}$)</th>
<th>Horizontal strain (mm·m$^{-1}$)</th>
<th>Damage level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>200</td>
<td>300</td>
<td>300</td>
<td>2.2</td>
<td>-2.0 ~ +1.6</td>
<td>I</td>
</tr>
<tr>
<td>2</td>
<td>250</td>
<td>250</td>
<td>280</td>
<td>1.6</td>
<td>-1.6 ~ +1.4</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>200</td>
<td>250</td>
<td>1.6</td>
<td>-1.6 ~ +0.8</td>
<td>I</td>
</tr>
<tr>
<td>4</td>
<td>350</td>
<td>150</td>
<td>250</td>
<td>1.6</td>
<td>-1.6 ~ +0.7</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>400</td>
<td>100</td>
<td>250</td>
<td>1.6</td>
<td>-1.6 ~ +0.7</td>
<td>I</td>
</tr>
<tr>
<td>6</td>
<td>450</td>
<td>50</td>
<td>250</td>
<td>1.6</td>
<td>-1.6 ~ +0.7</td>
<td>I</td>
</tr>
<tr>
<td>7</td>
<td>500</td>
<td>0</td>
<td>250</td>
<td>1.6</td>
<td>-1.6 ~ +0.7</td>
<td>I</td>
</tr>
</tbody>
</table>

![Figure 8: The excavation speed vs injection speed ((a) panel width 187 m; (b) panel width 127 m).](image)
Figure 9: Quantity of fly ash injected per month.

Figure 10: Concentration curve of slurry.

Figure 11: Water-cement ratio of slurry.
quantity in different mining speed of the shorten-width panel and the full-width panel.

3.3. POG Technology Application in Field Grouting Test

3.3.1. Observation in Grout Injection Engineering. Figure 5 shows the actual panel layout. The grouting quantity, the slurry concentration, and water-cement ratio in actual engineering are observed to verify the grouting scheme. Grouting quantity was recorded in real-time based on mixed water, fly ash, and the number of injection pumps. Figure 9 shows the actual quantity of injected fly ash per month (grouting engineering conducts from June of the first year to the January of the second year). With the mining length and width increased, the total quantity of fly ash injected per month was on the rise. Then, mining sites was gradually far from the open-off cut, the grouting quantity began to reduce based on the requirement for surface subsidence reduction ratio on POG technology scheme. The injected fly ash volume is only 98,912 t close to the prediction, and injection-production ratio \( a \) reaches 0.33 with the 540 m of excavation length based on field grouting statistic.

The concentration and water-cement ratio of slurry are the important indicators, which largely affect the slurry quantity injected. The supersaturated fly ash slurry was used in the field test due to the water-absorbing capacity of fly ash. Figures 10 and 11 show the concentration and water-cement ratio of fly ash slurry in actual engineering, respectively. The greater the water-cement ratio is, the longer the setting time will be. The concentration of the slurry injected was low to ensure the fine fluidity.

3.3.2. Surface Subsidence Control Effect and Verification by the Field Measurements. The grouting effects for protection villages are verified by the surface observations in stable state. Figure 12 shows the predicted and observed final surface subsidence with grouting. The subsidence is close to the predicted. The monitoring station J32 is the maximum permissible deformation of protection villages. Table 4 shows the surface observations compared with the maximum permissible deformation of protection villages with overburden grouting. The surface movement and deformation has been effectively controlled in village area. The protective constructions over the panel are within the first level damage, and the surface subsidence caused by coal excavation is controlled effectively.

Furthermore, the maximum subsidence in protection area is 92 mm, indicating the POG technology has a significant effect on subsidence control and reducing grouting quantity.

### Table 4: Deformation of villages with grouting and protection aim.

<table>
<thead>
<tr>
<th>Mining directly</th>
<th>Subsidence (mm)</th>
<th>Slope (mm·m⁻¹)</th>
<th>Horizontal strain (mm·m⁻¹)</th>
<th>Curvature (mm·m⁻²)</th>
<th>Horizontal displacement (mm)</th>
<th>Damage level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Villages</td>
<td>-92</td>
<td>0.7</td>
<td>0.64</td>
<td>-0.01</td>
<td>79</td>
<td>I</td>
</tr>
<tr>
<td>Target</td>
<td>—</td>
<td>≤3.0</td>
<td>≤2.0</td>
<td>≤0.2</td>
<td>—</td>
<td>I</td>
</tr>
</tbody>
</table>
the grouting difficulty and expand the application due to the grouting quantity reduction.

Overburden grouting technology combining with coal pillars has implemented in several coal mines in China; the results show that it has little affection on normal coal excavation and surface subsidence reduction ratio [17, 18]. However, the panel layout design only based on the dip direction of the panel can caused the low coal recovery production. The requirement of large grouting quantity increases the grouting difficulty. To some extent, it limits the applicability of the overburden grouting technology.

The innovative longwall panel layout method can effectively improve the coal production on the basis of surface subsidence control, due to POG technology design in dip and strike direction. Furthermore, it can optimize the existing technology and increase the applicability of the overburden grouting.

This paper provides a helpful reference for overburden grouting technology to control surface subsidence in the future. However, the mechanism and effects of surface subsidence control are considered by various factors and geological mining conditions. The grouting injection technology and long-term surface deformation extent of overburden grouting should also be considered in further studies.

5. Conclusions

In this paper, calculation of mining-induced surface subsidence due to overburden grouting and a partial overburden grouting mining method (POG) to control surface movement and deformation is proposed. The POG technology has been verified as an effective and economic method to design panel layout and mitigates the overburden failure. This technology involves in the Qi’nan Coal Mine in Anhui Province of China and demonstrates the benefits of the innovative panel layout method. In the process, overburden grouting equivalent calculation model (OGECM) is used to predict the surfaces subsidence with grouting to guide POG technology design.

The field testing indicates that surface deformation can be effectively mitigated and the coal recovery ratio is increased. The results of surface subsidence prediction and field measurement are in good agreement with each other.

The POG technology can reduce the grouting difficulty and save grouting costs on the basis of satisfying the surface buildings protective requirements. The overburden grouting equivalent calculation model (OGECM) proposed in this paper can effectively predict the surface deformation verified by the field measurements. Moreover, some successful grouting field measurements in China provide practical experience for grouting mining can be successfully controlled ground deformation.

Symbols

\( i \): Slope value (mm/m)  
\( K \): Curvature deformation (mm/m²)  
\( L \): Dip length of panel (m)  
\( L_b \): Horizontal displacement of bed separation (m)  
\( l \): Width of bed separation (m)  
\( m \): Excavation height of coal seam (m)  
\( n \): Index of the main influencing radius  
\( r \): Main influencing radius (m)  
\( \tan \beta \): Tangent of the main angle of influence  
\( u \): Horizontal migration (mm)  
\( V \): Mined-out coal volume (m³)  
\( V_g \): Injected fly ash volume (m³)  
\( W \): Surface subsidence value (mm)  
\( a \): Dip angle of coal seam (°)  
\( \eta \): Subsidence factor  
\( \varepsilon \): Horizontal deformation (mm/m).

Data Availability

The data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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References


