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*Original Research*

# Mitigating Land Subsidence Damage Risk by Fly Ash Backfilling Technology: an Injection Case in Overburden of Coal Mining

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**Abstract**

Most of the coal is used for thermal power generation in China, but a large number of fly ashes are produced after coal combustion. At present, the comprehensive utilization of fly ash is still insufficient, so it needs to find a new way of utilization. Meanwhile, large-scale underground coal mining leads to land collapse and ecological environment deterioration. The surface subsidence is the original source of mining damage, and that the efficient controlling subsidence method is backfilling in goaf with river sand, gangue and fly ash. In recent years, the backfilling technology has made great progress, and the backfilling position has developed from the traditional goaf to the internal overburden. In this method, the fly ash slurry is backfilled into the separation layer by ground drilling holes, which can actively control the surface subsidence and subsidence speed without affecting the normal coal production. Therefore, it has realized "Concurrent Mining and Reclamation" for protecting agricultural land. Finally, the surface dynamic subsidence calculation model is mentioned in this paper, which is suitable for this mining case. The results evaluate the effect of surface subsidence damage risk by fly ash.

**Keywords**: coal mining, fly ash, separation layer backfilling, subsidence calculation model, mitigating land subsidence

## Introduction

China is one of the world's biggest coal producers, most of which is used for thermal power generation. As the electricity consumption of cities and towns increases, more and more thermal power generations are built in the mining area for economizing transportation costs. Generally, about 250~300 kg fly ash is produced by burning one-ton coal [1], at present, fly ash has become the largest single solid pollution source in China, the fly ash output had reached 686 million tons in 2017, the output will be attained to three billion tons in 2020 [2]. Although fly ash has many potential comprehensive utilization values [3], the comprehensive utilization rate is still relatively low in China, so a new way for fly ash utilization needs to be found urgently.

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Large-scale underground mining will break the balance of ecological and living environments, for instance, land collapse, surface buildings damage and ecological environment deterioration [4]. Meanwhile, controlling surface subsidence is the core issue to mitigate the impact of mining on the environment. Also, many methods are existed to control surface subsidence [5, 6], for example, backfilling into goaf with river sand, gangue and fly ash [7-11]. However, normal backfilling methods require professional equipment and a large number of backfilling materials. It will not only increase manufacturing costs but also interfere with normal production. Therefore, exploring a new backfilling method is extremely necessary for economizing manufacturing costs.

Recently, the backfilling technology has made great progress, and that the backfilling position has developed from the traditional goaf to the internal overburden, which is a relatively new backfilling method [12-14], that is named Backfilling in Separation (BiS). This method is mainly applied in the special geological conditions, and the separation layer (Fig. 1) will be formed during the mining process. Finally, fly ash slurry is backfilled into the separation layer by ground drilling holes to control the surface subsidence and subsidence speed.

Also, BiS especially benefits to protect agricultural land. According to Chinese land protection law, the subsidence land must be reclaimed by coal mining enterprises, but the reclamation pattern is "First subsidence, second reclamation". This behaviour belongs to a passive "end management" pattern, which lacks a pattern of concurrent mining and reclamation [15, 16]. Thus BiS is suitable for concurrent mining and reclamation, and it actively controls surface subsidence and reduces the damage intensity of the surface subsidence to the agricultural land. BiS positively combines waste utilization, environmental-friendly mining, land protection, and reclamation, which achieves concurrent mining and reclamation as well.

According to the actual case, the dynamic subsidence calculation model is mentioned in this paper, which evaluates the effect of surface subsidence damage risk by fly ash.

## Experimental

### Calculation Model of Dynamic Surface Subsidence

Generally, the reduction rate is an index to evaluate the effect of mitigating surface subsidence sedimentation reduction. The BiS reduction rate is based on surface subsidence calculation value, so it needs the surface subsidence calculation model. There are many methods to calculate the surface subsidence [17-19], among which the Knothe influence function method is the most widely used in the world [20, 21]. This method has been applied in coal mines, metal mines, petroleum and other fields [22-24].

Therefore, to evaluate the effect of surface subsidence reduction during backfilling, which means that, it needs to calculate dynamic surface subsidence with Knothe thinking. Dynamic surface subsidence is surface subsidence in the mining process. In the calculation coordinate system (Fig. 2), calculation models of dynamic subsidence and speed are respectively described in Eq. (1) and (2). The other parameters are given in Eq. (3).

$$W(x)=\frac{W_{\mathrm{m}}}{2\arctan\frac{d+R}{a}}\left(\arctan\frac{d+R}{a}+\arctan\frac{R+x}{a}\right) \tag{1}$$

$$V(x)=\frac{V_{\max}}{1+\left(\frac{x+d}{a}\right)^{2}} \tag{2}$$

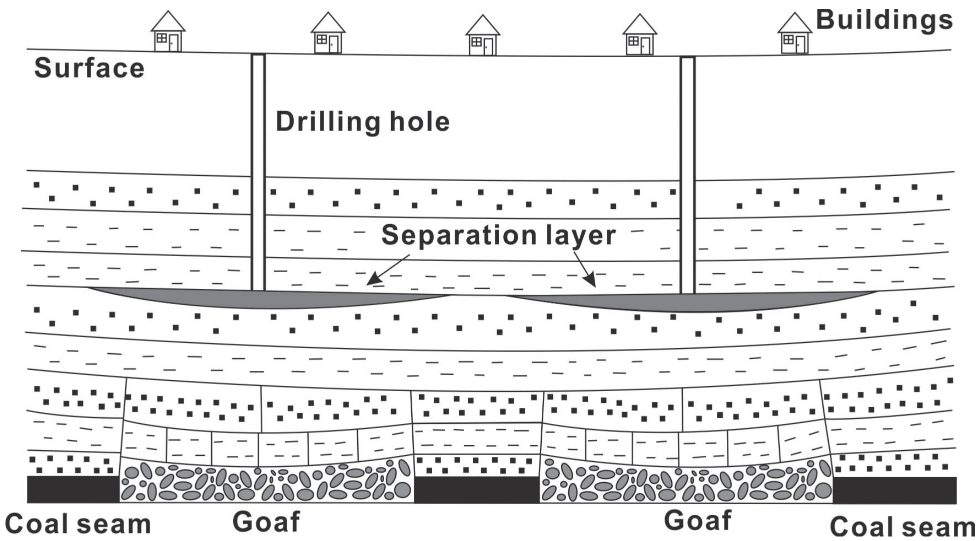


Fig. 1. Diagrammatic sketch of Backfilling in Separation.

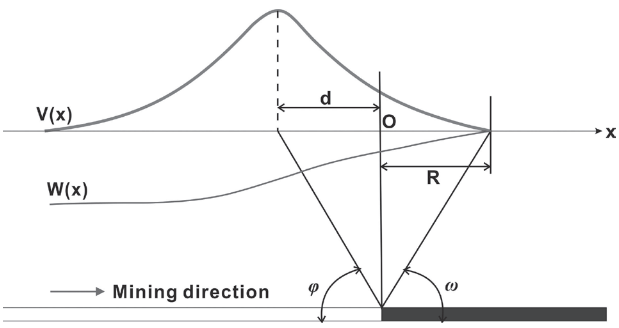


Fig. 2. Calculation coordinate system of surface dynamic subsidence.

$$\begin{cases} d = \dfrac{H}{\tan\varphi} \\ R = \dfrac{H}{\tan\omega} \\ V_{\max} = K\dfrac{CW_{\mathrm{m}}}{H} \\ a = \dfrac{W_{\mathrm{m}}}{V_{\max}} \times \dfrac{C}{\pi} \end{cases} \quad (3)$$

...where:

$W_m$- maximum subsidence of this working face; model parameter; *H*- mining depth *d*- a lag distance of maximum subsidence speed; *φ*- a lag angle of maximum subsidence speed; *β*- major influence angle; *ω*- advance influence angle; *R*- advanced influence distance; *x*- mining distance; $V_{max}$- maximum subsidence speed; *K*- surface subsidence speed coefficient; *C*- mining speed of the working face.

## Overview of the Case Area

### *Backfilling in Separation Introduction*

The research object is working face 307 (mining conditions are given in Table 1) and two working faces are on both sides of 307. A village is to the northeast of 307, and a bridge is 80m away from the mining boundary (Fig. 3).

However, mining of working face 307 will cause damage to the village and bridge. It was originally planned to relocate the village, but unfortunately, the negotiations regarding relocation compensation were not successful, so the village was not moved before mining. Finally, BiS was adopted to control surface subsidence for mitigating the damage of the village and bridge.

Generally, the separation layer form requires special geological conditions (Table 2). In this experiment area, it mainly formed between upper Jurassic and lower Permian Shihezi Formation, the strata are mainly composed of conglomerate, fine sandstone, medium sandstone, and mudstone, which benefit the formation of the separation layer.

Then backfilling materials will be injected in the separation layer through the two drilling holes (A1 and A2), which mainly consists of fly ash. Moreover, the particle size range of fly ash particles is 0.5~200μm, and its structure is composed of spheres, honeycombs, and blocks (Fig. 4). Sphere structure accounts for 60%

Table 1. Mining conditions of working face 307.

| Length (m) | Width (m) | Mining height (m) | Mining depth (m) | Dip angle (deg.) | Average mining speed (m/day) | Cumulative mining time (days) |
|---|---|---|---|---|---|---|
| 924 | 180 | 5.14 | 560 | 5.0 | 3.16 | 293 |

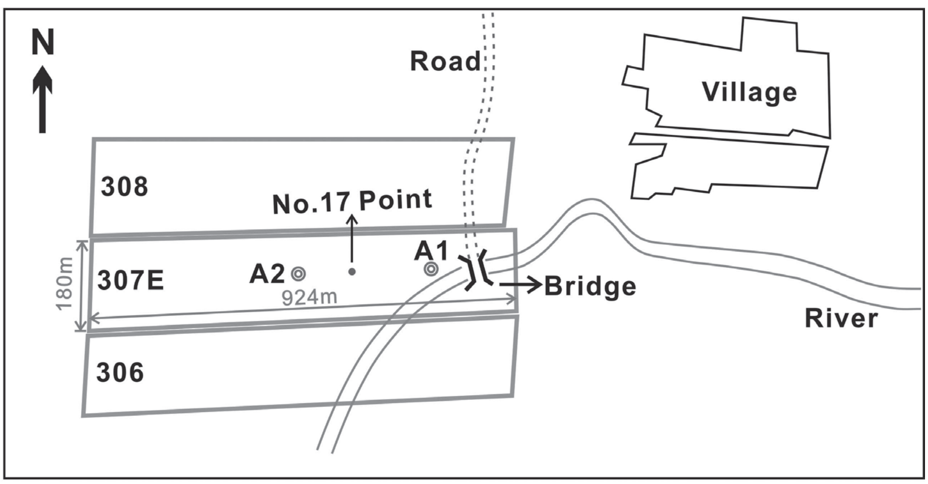


Fig. 3. Diagrammatic sketch of experiment area location.

Table 2. Geological conditions of working face 307.

| Strata | Thickness (m) | Lithology |
|---|---|---|
| Quaternary (*Q*) | 111.5 | Clay, sandy clay, sand, gravel |
| Upper Jurassic Mengyin Formation (*J*) | 241.2 | Medium and fine sandstone, conglomerate |
| Lower Permian Shihezi Formation ($P_1$) | 87.2 | Medium and fine sandstone, mudstone |
| Lower Permian Shanxi | 119.2 | Medium and fine sandstone, mudstone; coal seam |

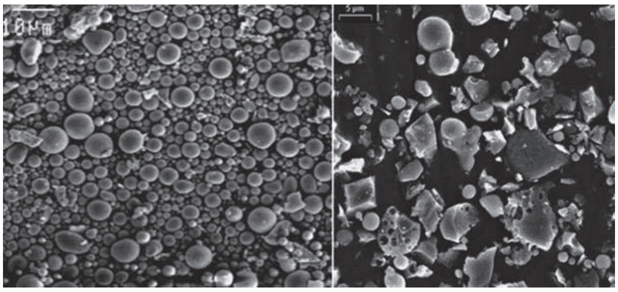


Fig. 4. Fly ash microstructure with 10 μm and 5 μm particle.

of the total, which benefits the pipeline transportation. It also has many chemical components, for instance, $SiO_2$, $Al_2O_3$, $Fe_2O_3$, and CaO.

Firstly, water injection is the primary part in the early stage of the backfilling process, and the maximum pressure of water injection is up to 20MPa in the early stage. Then those backfilling materials will be injected after water injection pressure reaching 5MPa. Finally, it total uses 38179 $m^3$ of water, 34271 $m^3$ of slurry (including 5138 tons of fly ash), and the total injection volume accounts for 24% of the mining volume.

*The Selection of Reference Point*

In all of the monitoring points, the maximum subsidence is at no. 17 point position. It is located between A1 and A2 backfilling holes, and 343m away from the mining boundary. The surface subsidence of no. 17 point is influenced by backfilling for three stages (Table 3): (1) backfilling in A1 hole: 49 days (from 92 days to 141 days); (2) without backfilling in A1 hole: 41 day (from 141 days to 182 days); (3) backfilling in A2 hole: 138 days (from 183 days to 321 days).

According to the China National Code [25], the surface subsidence speed is less than 1.67 mm/day, it means that surface subsidence is in the degenerating stage. Also, when the surface subsidence speed is less than 0.17 mm/day (surface subsidence less than 30 mm in six months), surface subsidence reaches a stable stage. In the last two observation activities (Fig. 5), their subsidence speeds respectively are 0.14 mm/day and 0.12 mm/day, which means no. 17 point has already reached a stable stage. Therefore, the no. 17 point is like the benchmark reasonable and representative.

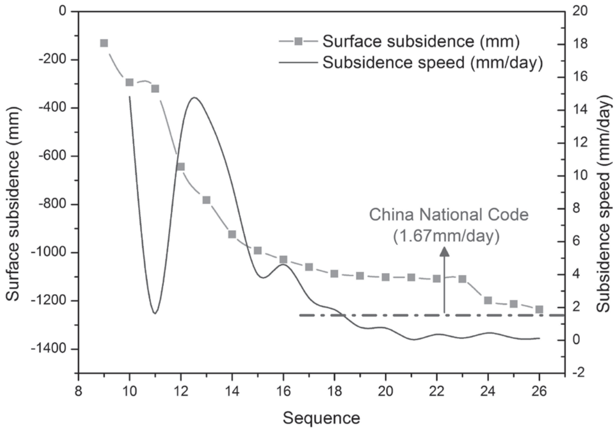


Fig. 5. Surface subsidence and subsidence speed curves of no. 17 point.

## Calculation of Dynamic Subsidence and Speed

Because working face 307 is still not in the condition of critical mining, so the maximum subsidence ($W_m$) is 1685mm by the Eq. (4).

$$W_m = mq \tag{4}$$

...where *m*- mining height; *q*- subsidence ratio coefficient.

According to the mining conditions of working face 307 (Table 1) and surface movement parameters (Table 4), the calculation parameters of dynamic subsidence and speed can be calculated by precondition, including $d$ = 150 m, $R$ = 204 m, $V_{max}$ = 27.4 mm/day, and $a$ = 62.1 m.

Therefore, the dynamic subsidence and speed models can be described with Eq. (5) and (6).

$$W(x) = 10.52 \times (80.05 - \arctan\frac{204+x}{62.1}) \tag{5}$$

$$V(x) = \frac{27.4}{1+(\frac{x+150}{62.1})^2} \tag{6}$$

In the early stage of A1 backfilling (Fig. 6), the subsidence reduction rate is not stable, because there

Table 3. Surface subsidence observation of no. 17 point.

| Sequence | Accumulative observation time (days) | Mining advance (m) | Observation subsidence (mm) | Subsidence speed (mm/day) | Stages |
|---|---|---|---|---|---|
| 1 | 1 | 0 | | | Start mining |
| 2 | 50 | 92 | | | A1 water injection |
| 3 | 75 | 163 | | | |
| 4 | 86 | 190 | | | |
| 5 | 92 | 200 | | | A1 backfilling |
| 6 | 102 | 240 | | | |
| 7 | 106 | 255 | | | |
| 8 | 117 | 287 | | | |
| 9 | 130 | 328 | 131 | | |
| 10 | 141 | 368 | 294 | 14.82 | A1 stops backfilling |
| 11 | 157 | 421 | 320 | 1.62 | |
| 12 | 183 | 524 | 644 | 12.46 | A2 backfilling |
| 13 | 193 | 570 | 782 | 13.8 | |
| 14 | 208 | 626 | 924 | 9.47 | |
| 15 | 225 | 690 | 992 | 4.0 | |
| 16 | 233 | 720 | 1029 | 4.62 | |
| 17 | 245 | 760 | 1060 | 2.58 | |
| 18 | 260 | 820 | 1088 | 1.87 | |
| 19 | 270 | 858 | 1096 | 0.8 | |
| 20 | 278 | 890 | 1102 | 0.75 | |
| 21 | 293 | 924 | 1103 | 0.06 | Finish mining |
| 22 | 307 | | 1108 | 0.36 | |
| 23 | 321 | | 1110 | 0.14 | A2 stops backfilling |
| 24 | 515 | | 1198 | 0.45 | |
| 25 | 621 | | 1213 | 0.14 | |
| 26 | 815 | | 1236 | 0.12 | Last observation |

Table 4. Surface movement parameters of working face 307.

| Subsidence ratio coefficient ($q$) | Tangent of major influence angle (tanβ) | Angle of advance influence (ω) | Lag angle of maximum subsidence (φ) | subsidence speed coefficient ($K$) |
|---|---|---|---|---|
| 0.33 | 1.70 | 70° | 75° | 2.88 |

is not enough injection of backfilling materials. Then when A2 starts backfilling, the subsidence reduction rate slowly increases to 15%. Finally, the stable rate is nearly 35% after enough injection of A1 and A2 backfilling.

In Fig. 7, the peak value of calculation speed appears in the third sequence, and then the speed declines rapidly to about 0.18mm/day. However, the observation speed appears in the eleventh sequence, namely that peak appears later than calculation and its maximum value is less than that of the calculation.

## Results and Discussion

The subsidence reduction rate is 35% of no. 17 point after backfilling, which is related to the calculation model, backfilling technology, backfilling materials,

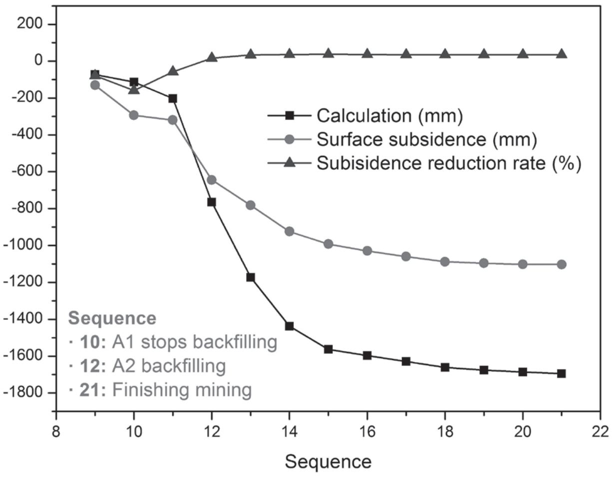


Fig. 6. Surface subsidence curves of calculation and observation of no. 17 point.

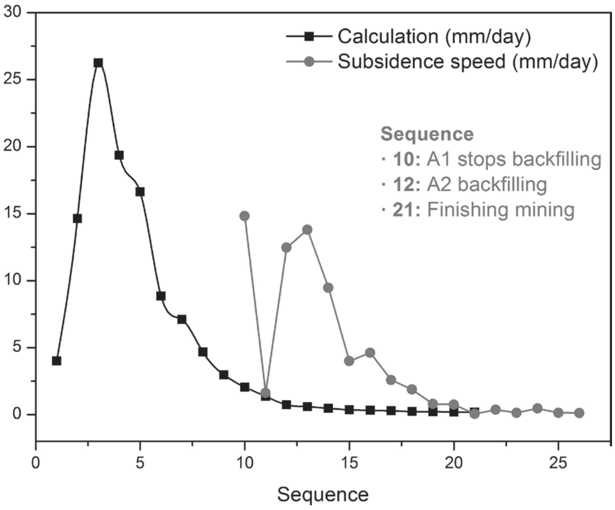


Fig. 7. Surface subsidence speed curves of calculation and observation of no. 17 point.

and relative position of monitoring point and a working face. The subsidence reduction rate is a comprehensive result, not a single one.

The calculation model does not have a unified model, but instead, there are many types of models. However, due to the differences in principles and parameters, their calculation results are also different [26]. The different results probably amplify the practical reduction rate, which will fail to effectively control surface subsidence. Therefore, an appropriate calculation model as the benchmark is extremely critical. Because model parameters are from data of the research area; thus, the calculation model from this paper is suitable for this research area and also as a benchmark is persuasive, but this model perhaps is not applicable in other research areas.

On the one hand, backfilling technology is an important factor to affect the subsidence reduction rate. Lag and pause of backfilling exist in the experiment, so the subsidence reduction rate is only 35%. The reason for this phenomenon is that backfilling lags mining for a long time, and surface subsidence will occur before backfilling. Perhaps backfilling and mining start simultaneously is the best choice to improve the subsidence reduction rate. In addition, fly ash is barely 15% in the slurry, which means that solid material is inadequate. Backfilling mainly depends on solid material, so it needs to improve the proportion of fly ash. However, toxic compounds from fly ash should be paid attention to avoid the pollution of groundwater.

On the other hand, the location of the monitoring point is another influencing factor as well. It considers that different locations have different subsidence reduction rates, namely that the reduction rate of subsidence centers should be minimum, and some places are away from subsidence centers should be larger. It conjectures 35% is supposed to be the minimum value in this experiment.

Finally, the maximum of actual subsidence speed appears later than that of calculation speed. Backfilling can delay the occurrence time of the maximum subsidence speed and reduce the surface subsidence speed at the same time. Slow surface subsidence can mitigate damage intensity to ground buildings [27, 28]. The other function of backfilling provides the possibility for the protection of ground buildings.

## Conclusions

(1) Backfilling in Separation (BiS) belongs to a relatively new backfilling method, which is to inject fly ash slurry into the overburden through surface drilling holes in the mining process. It can actively mitigate surface subsidence without affecting normal underground mining.

(2) According to the analysis of surface subsidence and subsidence speed in no. 17 point and calculation models, the results illustrate a stable subsidence reduction rate is 35% with BiS and also it delays the occurrence of maximum subsidence speed, which means that BiS effectively benefits decreasing surface subsidence and subsidence speed.

(3) BiS totally uses 5138 tons of fly ash in this case, which provides a new channel to consume wastes. Finally, it positively combines waste utilization, environmental-friendly mining, land protection, and reclamation, which achieves concurrent mining and reclamation as well.

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## Conflict of Interest

The authors declare no conflict of interest.

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