A study on the geometric effects of a concrete filling body in remaining roadways with fully mechanised caving

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Abstract
To address the problem of the concrete filling body (CFB) force failing to reach test strength in remaining roadways, the weakening effects due to aspect ratio and dimensional parameters on the actual CFB strength were investigated in this study. The geometric effects of CFB (including hoop and size effects) as well as the geometric effect coefficient determination method were analysed. Through laboratory tests and PFC numerical simulations, the hoop and size effect coefficients of the CFB in the Gaohu Coal Mine were studied. Furthermore, the calculation equations of actual strength and bearing capacity of the CFB were derived. Regarding the filling body failure and coal deformation in the remaining roadway located at the No. W1319 working face, the actual bearing capacity of CFB and surrounding rock stability during secondary exploitation were theoretically studied. The investigation suggests the adoption of a grouting reinforcement scheme for surrounding rock. The field applications performed have demonstrated that the deformation control effect in the remaining-roadway surrounding rock was effectively improved during second mining and the filling body beside the roadway suffered no additional damage. Studying the geometric effect of CFB can provide some theoretical guidance and industrial significance to accurately identify the filling body strength and reduce the failure risk of surrounding rock in remaining roadways.

Keywords: filling body beside roadway, geometric effect, hoop effect, size effect, surrounding rock control

1. Introduction
Remaining-roadway technology could realise pillar-free mining, providing obvious technical advantages in alleviating mining replacement tension and preventing corner gas over-limit and reducing coal loss (Kong et al. 2021). With the development of gob-side packing in a retained roadway, constant innovations are witnessed in filling materials beside roadways. A variety of materials such as high water, gangue and concrete have been applied in engineering practices and the controlling effect of surrounding rock has been improved continuously (Wang et al. 2020; Wu et al. 2020; Xie et al. 2020). Although the strength of filling body has reached the equivalent strength of C30 or even C40 concrete, failures due to the filling body and the severe deformation of the
surrounding rock of the gob-side retaining roadway still occur frequently. This is a technical problem that perplexes engineers and is not conducive to the development and promotion of the gob-side packing in retained roadways (He et al. 2020; Wang et al. 2020).

Many researchers have conducted substantial in-depth studies on the roadside backfilling body stability and remaining-roadway surrounding rock control. Based on the key block theory, some researchers have put forward mechanical models, such as size structure and lateral fracture structure, to calculate the supporting resistance for the remaining-roadway excavation, remaining roadway and secondary remaining roadway stages (Li et al. 2000; Hou & Li 2001; Wang & Hou 2001; Bai & Hou 2006; Li & Hua 2017). Using theoretical analysis methods, some researchers (Zhang et al. 2020; Zhang et al. 2020) have investigated the damage to direct roof and unbalanced bearing characteristics and proposed the surrounding rock control method for remaining roadways in thick coal seams. According to the properties of high mining faces and key block theory, some researchers (Han et al. 2019) have developed a calculation model for roadway-side support resistance, determined the internal connections between surrounding rock deformation and gob-side bearing resistance and established the surrounding rock control technology. A new type of anchor cable with constant resistance and large deformation was developed to solve the breaking of anchor cables and successfully applied to the remaining roadways after cutting the side of the hanging roof above a goaf (He et al. 2018).

Using rigid flexible combination carriers, some researchers (Tan et al. 2015) have proposed a support control technology combined with hard roof cutting technology and successfully applied it to the remaining roadways of thin coal seams. In the aforementioned studies, the criterion for determining the filling body damage centers on whether the calculated supporting force exceeds the experimentally measured uniaxial compressive strength of backfill in a laboratory (generally using a cubic test block). Due to the variation of mining height in engineering practices, most of the filling bodies beside roadways are rectangular and corresponding aspect ratios vary greatly in different projects. However, limited studies have been conducted on the effect of the filling body aspect ratio beside roadways on their bearing strengths. The ALPS method was developed to calculate the support resistance of roadway sides based on the analysis of roof collapse zones above the working faces. However, the determination of water flowing fractured zone height strongly relies on empirical formulas that could generate additional errors (Wu et al. 2018). During the identification of the CFB strength, the filling body strength is often determined based on the Code for Design of Concrete Structure, which is almost 50% lower than the cube compressive strength. As a result, the filling body strength was modified following the equation developed by Bieniawski to calculate the influence of aspect ratio on wall strength. Through the modified method, a concrete remaining roadway was successfully applied in the Jining No. 2 Coal Mine (Jia & Ma 2013). Wang (2011) developed a uniaxial compression numerical model for filling bodies beside roadways and analysed the stress variations at various aspect ratios, suggesting that the aspect ratio of filling body should not be greater than two. However, the quantitative relationship between aspect ratio and filling body has not been studied yet. It is worth noting that none of the aforementioned studies have analysed filling material heterogeneous properties and size effect, leading to the overestimation of the bearing capacities of filling bodies beside roadways. Therefore, the remaining roadway cannot be applied normally due to the destruction of the filling body beside the roadway.

Responding to the missing links identified in the previous studies, the geometric effects of CFB (including hoop and size effects) have been analysed in this research. The compressive strengths of prisms with aspect ratios of two were evaluated as the foundation strength of filling body beside roadway. On this basis, the conversion coefficient between cube strength and prism strength was obtained by experimental tests. In addition, a PFC particle numerical model was developed for the simulation of failure characteristics. Also, the strength variation rules and size effect coefficients of filling bodies beside roadways with different sizes were obtained through the fitting process. Furthermore, the failure of filling bodies beside roadways of the W1319 working face in the Gaohe Coal Mine was analysed, providing theoretical and practical significance to accurately identify the strength of filling bodies beside roadways, and reduce the failure risk of the surrounding rock of a gob-side retaining roadway.

2. Analysis of the geometric effects of CFB

To ensure filling body stability, the filling body strength should be greater than the supporting resistance. In reality, even after taking certain safety factors into consideration, filling body failures still occur frequently. Taking the work reported in the study by Feng et al. (2019) as an example, and based on theoretical calculations, the supporting resistance at the roadway side of the No. 3307 working face was identified at 11.23 MPa. It is worth mentioning that this theoretical calculation method has been verified by other researchers (Han et al. 2015; Kan et al. 2018). In addition, the CFB strength was about 20–25 MPa with a safety factor of about two, assuming that the filling body beside the roadway was able to meet the safety requirements. After the construction, the filling body demonstrated serious central bulge deformations along with severe roadway-side roof subsidence and horizontal deformations, indicating that the filling body failed to bear the overburden load and the actual strength of the filling body.
did not meet the design requirements. In other words, CFB intensity was overestimated.

Often the overestimation of CFB actual strength is due to two main reasons: the hoop effect and size effect. Since these two factors are related to filling body geometric parameters, they are collectively referred as the ‘geometric effect’. The filling body geometrical effect leads to far lower actual strengths than experimentally obtained ones, making it difficult for filling body to bear roof load, resulting in damage and ultimately roadway deformation. In conventional compression experiments, the friction forces between specimen and upper and lower loading plates were increased as the normal stress rises (Kaga 1968), which gradually formed lateral constraints on specimen upper and lower surfaces. Specimens tended to damage the top cone, resulting in higher experimental (actual) strength than theoretical strength (strength when there was no friction between test specimen and upper and lower loading plates). The strengthening effects of upper and lower loading plates on the experimental strength of a specimen is known as the hoop effect (Li et al. 2016).

In the bearing system of the roof-CFB-floor, the CFB was considered as a test specimen, while the roof and floor were assumed to be the upper and lower loading plates, respectively. With the rotation and sinking motions of basic roof, the normal stress and frictional constraints of roof and bottom plates on the filling body continuously increased and the filling body actual strength was higher than the theoretical strength. However, the hoop effects of upper and lower loading plates were not infinite. In general, the hoop effect mainly acts on the part of the specimen boundary within 45° inward. In other words, when the specimen height exceeded twice its width, the hoop effect of the middle part of the specimen disappeared and its strength became very close to its real strength. The width and height of CFB changed with the transformation of mining height parameter. When the filling body aspect ratio was greater than two, the actual strength of the middle part of the filling body became very close to its theoretical strength, but remained lower than its laboratory test strength.

On the other hand, the CFB is a heterogeneous material prepared by the mixing and solidification of cement slurry and aggregate, where size effect plays a significant role (Xu et al. 2016). However, in underground construction, on-site batching and manual feeding are preferred to the commercial mixing mode, which is commonly adopted in surface construction, leading to more serious heterogeneity of CFB. In reference (Feng et al. 2019), the height and width of the filling body were 3.2 and 1.4 m, respectively, resulting in an aspect ratio of greater than two. Due to the geometrical effect of the filling body, the actual strength of the filling body in local areas was lower than the supporting resistance, leading to the deformation and failure of the filling body.

Therefore, three coefficients were defined to determine the relationship between the filling body’s real strength and cube strength, including the hoop effect coefficient, the size effect coefficient and geometric effect coefficient. The hoop effect coefficient was calculated by compressive strength ratio of prismatic specimens with an aspect ratio of two to cube specimens with the same section. The size effect coefficient was computed by the compressive strength ratio of a specimen of a certain size to that of prismatic specimens with aspect ratio of two. The last coefficient known as the geometric effect coefficient can be determined by the product of hoop and size effect coefficients.

2.1. Loop effect coefficient of filling body beside roadway

Due to the filling body hoop effect, at a constant compression area of the filling body, an increase in the filling body height tends to decrease its actual strength. By increasing the filling body aspect ratio from one to two, the strength of the filling body gradually decreased from the cube strength tested in the laboratory to its theoretical strength. When the filling body aspect ratio reached two, its height altered the influence of friction between the roof and floor, and meanwhile the strength of the middle part of the filling body became extremely close to the theoretical strength. According to concrete specimen tests previously conducted by the Ministry of Railways, the compressive strength of concrete specimens remained almost unchanged at aspect ratios of greater than two. Similarly, the strength of the filling body remained at a constant value when its aspect ratio was greater than two. Therefore, the strength (also known as axial compressive strength) (Vincent & Ozbakkaloglu 2013) of the specimen with the aspect ratio of two (test specimen size with dimensions 100 × 100 × 200 mm or 150 × 150 × 300 mm) was taken as a design indicator for the strength of roadway backfill. The axial compressive strength of the filling body with an aspect ratio of two was defined as $f_c$, with cubic specimen compressive strength denoted as $f_{cu}$ and hoop effect coefficient considered as $\alpha_n$, whose relation was expressed as:

$$\alpha_n = f_c / f_{cu}. \quad (1)$$

The hoop coefficient $\alpha_n$ could be obtained after determining axial compressive strength $f_c$ and cube compressive strength $f_{cu}$ through laboratory tests.

2.2. Size effect coefficient of CFB

Due to the large size of CFB, it was difficult to conduct full-size model tests on a filling body with existing test equipment. By performing more in-depth studies and due to the development of numerical simulation technology, the application of the inversion of material meso-parameters to study the mechanical properties of macroscopic structures has grown (Wu & Xu 2016). In this paper, a discrete
element software known as PFC2D was adopted to analyse the size effects of filling body materials and the simulation process is shown in figure 1. The process was mainly divided into two parts: the calibration of the meso-parameters of standard prism specimen and the simulation of the multi-scale uniaxial compression of filling body. For the calibration of meso-parameters, first, the proportions of cement slurry and coarse aggregate were determined according to filling body material ratio and a specimen model was established. Then, the stress–strain curve of the standard prism specimen under uniaxial compression was drawn based on the results obtained from uniaxial compression tests. Finally, a meso-parameter inversion was performed until the stress–strain curves of simulated specimens became basically consistent with those obtained from laboratory tests. It is worth mentioning that gravity stress was not considered during the calibration of the meso-parameters. The second part of the process was the simulation of multi-scale uniaxial compression of a filling body. By changing model size and considering gravity stress, a number of multi-scale uniaxial compression tests were performed to analyse the failure characteristics, stress–strain curves and peak strength change in the filling body.

3. Calculation of geometric effect coefficient

Taking CFB in the Gaohe Coal Mine as an example, the geometric effect of CFB was analysed to provide a basis for checking filling body strength.

| Table 1. Material performance parameters of roadside packing |
|-----------------------------------------------------------|
| Material parameters | Slump (mm) | Set time (min) | Axial compressive strength (MPa) |
|---------------------|------------|----------------|---------------------------------|
| Value               | 192        | 185            | 280                             |
|                     |            | Initial        | Final                           | 3 d | 28 d |
|                     |            | 10.76          | 24.49                           |

### 3.1. Hoop effect coefficient

The physical parameters of the test specimen are shown in Table 1. According to the filling body material proportions, the mixture was prepared in a laboratory and uniaxial compressive strength tests were performed at 3, 7 and 28 d. The specimens were tested on a MTS testing machine. The dimensions of cubic and prism specimens were $150 \times 150 \times 150$ mm and $150 \times 150 \times 300$ mm, respectively. The test results are presented in figure 2.

Following equation (2), a number of regression analyses were conducted on the experimentally obtained results for axial compressive strength $f_c$ and cube compressive strength $f_{cu}$ of filling body materials.

$$f_c = 0.7197f_{cu} \left( R^2 = 0.9761 \right). \quad (2)$$

Based on the regression analysis, the conversion coefficient $\alpha_n$ between the axial and cube compressive strengths of filling body was obtained at 0.72.
Figure 2. Regression analysis of $f_c$ and $f_{cu}$.

Table 2. Proportions of concrete ingredients

| Material            | 5–10 mm | 10–16 mm | 16–20 mm |
|---------------------|---------|----------|----------|
| Conventional C30 concrete | 9.8     | 9.8      | 9.8      |

Table 3. Meso-parameters of PFC numerical simulation of roadside packing materials

| Parameters          | Cement slurry | Aggregate |
|---------------------|---------------|-----------|
| Normal strength (MPa) | 15.6          | 31.8      |
| Normal stiffness (GPa) | 25            | 60        |
| Shear strength (MPa)  | 24            | 38        |
| Shear stiffness (GPa) | 8.9           | 16.3      |
| Bonding radius (mm)  | 1             | 1         |
| Porosity             | 0.12          |           |
| Friction coefficient | 0.6           |           |
| Particle radius (mm) | 0.5–1         | 2.375–4.75/4.75–9.5 |

Figure 3. Meso-mechanical model and uniaxial compression test curve.

3.2. Size effect coefficient

3.2.1. Establishment of PFC model and calibration of meso-parameters. The CFB strength grade in the Gaohe Coal Mine was C30, with the cement slurry and coarse aggregate volumes accounting for 70.6 and 29.4%, respectively. To facilitate the formation of aggregate, sand and cement were applied as cement slurry particles. The coarse aggregate was continuous graded gravel with particle size range of around 5–20 mm. Based on the particle size the coarse aggregate was divided into three size ranges. The ratio of each size range of coarse aggregate is given in Table 2. The numerical model established based on aggregate proportion is shown in figure 3.

During the uniaxial compression tests, the calculation continued until the compression value reached half of the peak intensity of the attenuation value. As demonstrated in figure 4, a detailed specimen failure process, the gray particles are cement slurry particles while the blank irregular blocks are coarse aggregate with the black lines or areas representing the cracks generated during compression failure process and the damage generated due to crack propagation. From figure 4, at 0.6 times the peak stress, some tiny cracks started to appear at the interface of coarse aggregate and cement slurry, which is known as the crack initiation stage (a). When at 0.8 times the peak stress, crack developments began to accelerate in the cement slurry and were mainly distributed in the specimen edge, which was called the crack expansion stage (b). When the peak stress was reached, several cracks...
were created inside the specimen, which then expanded and penetrated to gradually damage the upper edge of the specimen, which is known as the crack penetration failure stage (c). After peak stress, the loading plate continued to shift. Despite the fact that the stress stopped increasing, cracks continued to expand and specimen strength rapidly decreased, demonstrating obvious brittle failure, which is called the post-peak failure stage (d).

3.2.2. Multi-scale uniaxial compression test. Considering the gravity field effect, large specimen models were established with 4, 8 and 12 times the standard prism specimen height (150 × 300 mm) and the aspect ratio was kept at two. The ratio between the height of large-scale simulation specimen and that of the standard prism specimen was called height magnification (N). Also, the ratio of the strength of the large simulated specimen σₙ to that of the standard specimen σ₀ was defined as the size effect coefficient ξₙ. The simulation parameters are summarised in Table 4.

The uniaxial compression stress–strain curves of simulated specimens with various height expansion multiples N are displayed in figure 5a and the size effect coefficient is shown in figure 5b. According to figure 6, the peak strength demonstrated in the uniaxial compression stress–strain curve of the simulated specimen continuously decreased with the increase in height expansion multiples N, suggesting that the actual strength of filling body decreased with the size increase. The uniaxial compressive strengths of large specimens with N = 4, N = 8 and N = 12, were 0.92, 0.86 and 0.825 times that of the standard prism specimen, respectively. The slope of the curve in the pre-peak stage slightly decreased with the increase in height expansion multiples N, indicating that specimen deformation modulus slightly dropped. The peak strength strain of the specimen occurred slightly before the height expansion multiples N increased, indicating that resistance to the deformation of specimen dropped. Based on the data presented in figure 5b, the size effect coefficient of the specimen was approximately linearly correlated with its height ratio. The relation between the two was expressed as

$$\xi_N = -0.0156N + 0.9986 \quad (R^2 = 0.95).$$

3.3. Geometric effect coefficient and bearing capacity of the filling body

Based on these laboratory tests and numerical simulations, the equation for the geometric effect coefficient of filling body was obtained and is shown as

$$\beta = -0.0112N + 0.7187.$$
The calculation of the bearing capacity $F_b$ of filling body was performed using equation (5):

$$F_b = \beta f_{cu} t_d.$$  \hspace{1cm} (5)

4. Engineering application

4.1. Engineering overview

The No. W1319 working face of the Gaohe Coal Mine is mined without coal pillars. The height and width of the remaining roadway were 3.85 and 4 m, respectively, with a 3.8 and 1.5 m filling body. It was found that, after leaving the mining roadway in the previous working face, a lot of damage formed in local areas of the filling body with perforation cracks generated in critical areas and severely deformed surrounding coal. Figure 6 shows the detection results of drilling holes in the remaining roadway of working face No. W1319, demonstrating that the roadway roof was broken within a range of about 7.4 m and the coal wall was broken to varying degrees within a range of about 10 m. Overall, the remaining-roadway surrounding rock was broken, resulting in high risks of severe damage in the case of secondary mining.

4.2. Stability control scheme and application effect of roadway surrounding rock

According to relevant remaining-roadway theories, when the bearing capacities of the coal wall and filling body are greater than the load applied by the basic roof structure, the remaining-roadway surrounding rock often stays stable (Luan et al. 2018; Zheng & Duan 2019). The basic roof structure and bearing structure are shown in figure 7.

The load $F_m$ applied to the base roof structure was determined using the following equation:

$$F_m = \frac{n q_0 + \gamma_m H_m - L^2}{2L - x_b - l_c - l_d} + [\gamma_c (h_t + \gamma_c (m - h_a))] (x_b + l_c + l_d),$$  \hspace{1cm} (6)

where $q_0$ (MPa) is the distributed load of soft strata on the key block B of base roof; $\gamma_m$, $\gamma_c$ and $\gamma_i$ (kN m$^{-3}$) refer to the average volume forces of the basic roof rock, direct roof rock and top coal, respectively; $n$ indicates the multiple of superimposed stress during secondary mining, generally in the range of 3–7; $L$ (m) is the lateral fracture step of basic roof; $x_b$ (m) means the lateral fracture depth of basic roof; $l_c$ and $l_d$ (m) denote the widths of roadway and filling body, respectively; $m$ (m) represents the coal thickness and $h_a$ (m) is the filling body height.

Bearing capacity of coal seam was calculated following equations (7–9) (Hou & Ma 1989).

$$F_c = q_s x_s + \int_0^{x_s} \sigma_z (x) dx,$$  \hspace{1cm} (7)

$$q_s = \frac{\pi d^2 \sigma_s}{4 D_a D_b} \frac{1 + \sin \varphi}{1 - \sin \varphi} + \sigma_c,$$  \hspace{1cm} (8)

$$\sigma_z (x) = \left( \frac{\epsilon_0}{\tan \varphi_0} + \frac{1 + \sin \varphi}{\tan \varphi_0} + \frac{\sigma_c}{\tan \varphi_0} \right) \times \exp \left( \frac{\tan \varphi_0 + \sin \varphi}{h_a} \left( \frac{1 - \sin \varphi}{h_a} \right) \right) - \frac{\epsilon_0}{\tan \varphi_0},$$  \hspace{1cm} (9)

where $q_s$ (MPa) refers to the anchorage composite carrier strength, $d$ (m) is anchor bolt diameter, $\sigma_c$ (MPa) stands for the anchor bolt yield strength, $D_a$ and $D_b$ (m) denote the spacing of bolt and row, respectively, $x_s$ means anchorage composite carrier thickness obtained as
\[ x_s = l_s - 0.5 \max (D_s, D_b) \] with \( l_s \) (m) being the anchor bolt effective length, \( c \) and \( c_b \) (MPa) indicates the cohesion of coal and contact surface, and \( \varphi \) and \( \varphi_b \) are internal friction angles of coal and contact surface, respectively. During secondary mining, the coal within the fracture position of basic roof basically stayed in the post-peak residual stress state. The uniaxial compressive strength \( \sigma_{c0} \) of coal degenerated into residual strength \( \sigma_{cb} \) (Huang et al. 2018), residual cohesive force \( c_b \) and residual internal friction angle \( \varphi_b \), respectively.

To maintain the wall rock stability in the remaining gateway, the principal \( F_s + F_c > F_m \) should be satisfied. This equation can be rewritten as \( F_0 > F_m - F_c = [F] \). In other words, the backfill bearing capacity should be higher than the load acting on it \([F]\). According to the theoretical and experimental studies on the No. W1319 working face, the following parameters were obtained including \( q_0 = 0.44 \) MPa, \( \gamma_m = \gamma_l = 25 \text{ kN m}^{-3} \), \( \gamma_s = 15 \text{ kN m}^{-3} \), \( n = 7 \), \( L = 29.9 \) m, \( x_s = 4.76 \) m, \( l'_c = 4 \) m, \( l'_l = 1.5 \) m, \( m = 6.5 \) m, \( h_s = 3.85 \) m, \( d = 0.022 \) m, \( \sigma_{c0} = 500 \text{ MPa} \), \( D_s = 0.8 \) m, \( D_b = 0.9 \) m, \( x_s = 1.85 \) m, \( l_l = 2.3 \) m, \( c_b = 0.1 \text{ MPa} \), \( \varphi_0 = 10^\circ \), \( \sigma_{cb} = 1.21 \), \( c_b = 0.42 \) and \( \varphi_b = 20.5^\circ \). After substituting these parameters into equations (6–9), \([F] = 35.9 \) MN was obtained. According to equation (5) for the geometric effect coefficient, the geometric effect coefficient of filling body at working face No. W1319 was 0.577 with a cubic strength of C30 for the filling body ranging from 30 to 35 MPa, backfill actual strength ranging from 17.31 to 20.20 MPa and bearing capacity ranging from 25.97 to 30.30 MN. Therefore, the conclusion \( F_d < [F] \) was obtained, indicating that after the secondary mining, the filling body was no longer stable and the remaining-roadway bearing structure was damaged and unstable.

Since the backfill load-bearing capacity \( F_d \) was a constant value in this study, reducing the load \([F]\) acting on filling body to address the problems of failure and instability of the remaining gateway bearing structure in the No. W1319 working face became necessary. Through the analysis of \([F] = F_m - F_c\), increasing the load-bearing capacity \( F_c \) of the coal wall by strengthening its structure was beneficial to reduce the load \([F]\) acting on filling body. The existing grouting agent of the Gaohe Coal Mine was Jin’an reinforcement No. 1. After grouting, the coal strength could be restored to about 0.8 times the strength under an undisturbed stress state. By substituting relevant parameters into equations (6–9), the load on the filling body after coal grouting was determined at 14.21 MN, which met the stability requirements of the remaining gateway load-bearing structure, suggesting that the CFB was not damaged and the remaining gateway surrounding rock remained stable.

Grouting reinforcement was one of the most effective methods to resolve the issue of broken surrounding rock. However, the calculation theory for grouting depth was still lacking. Technicians often estimate the effective grouting depth according to the broken range of a roadway. For the remaining roadway, the side coal body between the roadway surface and the basic roof fracture line is the effective bearing body to carry the load of the overlying strata, and the coal body in other areas plays a limited role in maintaining the surrounding rock stability of a remaining roadway. To enhance the loading capacity of the whole coal wall, grouting hole depth should be greater than the lateral fracture position of a basic roof. Two 5-m deep grouting holes were arranged at 2-m spacing in each row, with the grouting hole pressure adjusted according to the existing situation. The layout of grouting holes is displayed in figure 8.

To evaluate the efficiency of the scheme, a number of surface displacement measuring stations were arranged 280 m away from the open cutting in the No. W1319 air.
5. Conclusion

(i) To address the failure CFB force failing to meet the laboratory test strength in remaining roadways, the effects of aspect ratio and dimensional parameters on CFB actual strength were evaluated in detail. The CFB geometric effect, including both hoop and size effects, was analysed and the determination methods for geometric effect, hoop effect and size effect coefficients were established.

(ii) Taking CFB in the Gaohe Coal Mine as the case study, the hoop effect and size effect coefficients were determined by laboratory tests and numerical simulations. In addition, the calculation equations of the actual strength and bearing capacity of filling body were derived.

(iii) To investigate the backfill failure and coal deformation in the remaining gateway of the No. W1319 fully mechanised caving face in the Gaohe Coal Mine, the actual bearing capacity and load-bearing of filling body were calculated, revealing that maintaining the stability of surrounding rock and filling body during secondary mining was challenging. However, based on these findings, a surrounding rock control plan was proposed and successfully applied in the field.

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