Combined support technology for main roadway passing through goaf: A case study

Dongdong Chen | Qing Zhang | Shengrong Xie | Zaisheng Jiang | Yubo Li | Mingming Gao | Hui Li | Xiaoyu Wu | En Wang | Songhao Shi | Long Wang

1School of Energy and Mining Engineering, China University of Mining and Technology-Beijing, Beijing, China
2Beijing Key Laboratory for Precise Mining of Intergrown Energy and Resources, China University of Mining and Technology-Beijing, Beijing, China
3Consulting Center of China National Coal Association, Beijing, China

Correspondence
Shengrong Xie, School of Energy and Mining Engineering, China University of Mining and Technology-Beijing, Beijing 100083, China.
Email: xsrxq@163.com
Qing Zhang, School of Energy and Mining Engineering, China University of Mining and Technology-Beijing, Beijing 100083, China.
Email: 1981701489@qq.com

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Abstract
Controlling the surrounding rock of the main roadway passing through a goaf during the reconstruction and expansion of a merger and reorganization mine is a common challenge in underground mining practices. In this study, a combined support technology of roof “anchorage-mesh-shotcrete” and a double-H-type space frame structure for a main roadway passing through a goaf was studied using field investigations, theoretical analysis, and engineering practice. It was observed that the main roadway control difficulties lie in the strongly mining-induced roof strata in the early stages, with collapsed gangues not connected to an unsupported roof, large goaf sections, and multiple superpositions of surrounding rock stress fields with complex distributions. Based on the results, a double-H-type space frame structure support system comprising a “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam” was constructed. This provided strong pillar support, enhanced the shock resistance of the roof, improved the bending and lateral pressure resistances of the frame structure, and produced airtight spaces for the main roadway. Accordingly, a “double systems” support scheme was designed. The results of the engineering practice indicated that the deformation of the goaf roof and force of the supporting structure were controlled within a safe range, meeting the requirements for mine ventilation, pedestrians, and haulage. Consequently, the surrounding rock control problem for the main roadway passing through the goaf was effectively solved, and theoretical and technical bases were provided for the stability control of a roadway passing through a goaf under similar conditions.

KEYWORDS
construction of airtight spaces, double-H-type space frame structure support system, Main roadway passing through goaf, reducing span control, roof “anchorage-mesh-shotcrete” support
1 | INTRODUCTION

The merger and reorganization of coal enterprises can integrate mines with low production capacity and outdated technical equipment into a modern mining company with green operation, improved safety, high production, and high efficiency. Nevertheless, because of arbitrary mining and excavation, a large number of goafs with unknown locations and scopes have been left in the mine fields of merger and reorganization mines. Thus, the corresponding roadways are faced with problems such as complex stress environments, deterioration of the surrounding rock, and the need to pass through the goaf during the reconstruction and expansion of the merger and reorganization mine. These seriously affect the safety and production of the modern mine.

In recent years, many mining science and technology workers have researched the control mechanisms and technologies of roadway surrounding rock under complex geological conditions such as large sections, soft surrounding rocks, and composite roofs. To control the surrounding rock of a large section of a roadway, Xie et al. studied the failure mechanisms of a large section of a chamber under a 1200-m deep goaf and proposed a comprehensive control technology. Hao et al. applied an innovative equivalent width support technology for a large section of roadway in a thick coal seam based on a theoretical analysis, experiments, and applications. Gao et al. revealed the roof fall mechanism of an ultra-large section full-seam chamber and proposed a control technology of grouting reinforcement and high-strength anchor bolt and anchor cable support. In terms of the surrounding rock control of a soft rock roadway, Kang et al. analyzed the effects of anchor bolts and anchor cables in suppressing the cracking and dilation of the soft surrounding rock and proposed an improvement to the rock bolt system. Shen assessed the stability and deformation of a soft rock roadway under different roof support schemes and determined a new roadway support design. This new design adopted an optimal anchor bolt and anchor cable arrangement with high pretension and full-length grouting. Qin et al. clarified the factors influencing the stability of the surrounding rock of a deep soft rock roadway under dynamic pressure and proposed a coupling reinforcement support scheme. Sun et al. studied the jet grouting technique for improving the soft coal mass to control the large deformation of roadways. In terms of surrounding rock control for a composite roof roadway, Xie et al. explored the mechanical properties and energy dissipation laws of coal-rock structures with different height ratios and revealed the support principles for a coal-rock composite roof. He et al. studied the structural characteristics of a composite roof and the effects of roof cutting under the composite roof and then used engineering practice to verify the research results. Xiong et al. derived an expression for a comprehensive influence coefficient for a composite roof, based on the influence of each main factor on the stability.

These studies enriched the control theories for the roadway surrounding rock under complex geological conditions and have important practical value. However, studies on the support mechanisms and technologies for the surrounding rock of a main roadway passing through a goaf have rarely been conducted. A coal mine of the Shanxi coal transportation and sales group is a merger and reorganization mine, and there are many goafs with unknown locations and scopes in the area of the auxiliary shaft station. Moreover, some goafs were exposed during the mine field development. The main roadway passing through the goaf was supported based on the traditional support theory and technology. However, it was basically unable to meet the requirements of mine safety. Hence, there is an urgent need to propose a targeted support technology for the surrounding rock control of the main roadway passing through the goaf. This study proposed a “double systems” support technology that included high-strength roof “anchorage-mesh-shotcrete” and a double-H-type space frame structure consisting of a “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam.” This combined support technology was successfully applied in engineering practice. Thus, the effective control of the surrounding rock of the main roadway passing through the goaf was realized.

The combined control technology proposed in this paper enriches and develops the control methods for the surrounding rock of a roadway under complex conditions, thereby providing an important reference for the control of roadways passing through goafs under similar conditions.

2 | GEOLOGICAL SETTING

A coal mine of the Shanxi coal transportation and sales group is a merger and reorganization mine, and it was mainly formed from an original Liujiamiao coal mine with a production capacity of 0.15 Mt/a, original Hengxiang coal mine with a production capacity of 0.30 Mt/a, and original Shiyanhe coal mine with a production capacity of 0.21 Mt/a (Figure 1A). Furthermore, the industrial sites for the main and auxiliary shafts of the original Shiyanhe coal mine act as those for the main and auxiliary shafts of the coal mine, respectively. The industrial site of the original Liujiamiao coal mine is used as that for the return air shaft of the coal mine. The mine field area of the coal mine is 10.4136 km², and it has a production capacity of 1.20 Mt/a and service life of 40.01 years. At present, the coal mine is in the mine field development stage, and the mining seams are the No. 3 coal seam, No. 9 coal seam, and No. 15 coal
Chen et al. The buried depth and dip angle of the No. 3 coal seam at the bottom of the Shanxi Formation are 150 m and 4°-8°, respectively, indicating a nearly horizontal coal seam.

A large number of goafs with unknown locations and scopes and abandoned roadways were left in the auxiliary shaft station in the merger and reorganization mine (Figure 1B). Furthermore, the different sizes of goaf #1, goaf #2, and goaf #3 were exposed in the excavation processes for passing chamber 1, passing chamber 2, and the main auxiliary haulage roadway, respectively. The sizes of goaf #1 and goaf #3 are 30.5 m × 15 m (length × width) and 23.5 m × 17 m (length × width), respectively. The test main roadway passes through goaf #1. The distribution of goaf #1 and the failure of the main roadway passing through the adjacent goaf #2 are shown in Figure 2. The roof strata of goaf #1 exhibit a ladder pattern of caving, and the cracks are extremely developed. The average heights of goaf #1 and the collapsed gangues are 7 m and 3.5-4.0 m, respectively. The average thickness of the No. 3 coal seam in this region is 3.5 m. The coal seam is characterized by black coal, a massive structure, softer coal quality, and fragmentation from the drilling core. The lithologic distribution of the borehole histogram is presented in Figure 3. The roof strata are mainly composed of sandy mudstone, siltstone, mudstone, and fine sandstone, whereas the floor strata are mainly composed of sandy mudstone, mudstone, and fine sandstone. The test main roadway has a rectangular shape, with a size of 5.0 m × 3.5 m (width × height) and a sectional
area of 17.5 m². The positional relationship between goaf #1 and the test main roadway is shown in Figure 4.

3 | CONTROL DIFFICULTIES AND TECHNOLOGY FOR MAIN ROADWAY PASSING THROUGH GOAF

The control difficulties for the main roadway passing through the goaf were analyzed based on the production and geological conditions of the auxiliary shaft station, and the spatial relationship between the main roadway and goaf in the merger and reorganization mine. The results are as follows.

1. Strong mining in early stages: The rock strata were influenced by strong mining in the early stages, resulting in the beginnings of a gradual collapse upward, and the expansion of the failure zone. The roof strata within a certain depth in the overlying strata were in the caving and fracture zones, and the roof was in a state of “no support” for a long time (Figure 2D). The shallow surrounding rock is extremely broken and basically has no bearing capacity, contributing to the bed separation instability, and even large-scale roof fall.

2. Collapsed gangues not connected to goaf roof: The height of the collapsed gangues is less than that of the goaf, and the roof hangs. In addition, the free surface of the roof is increasing, and it is in a fragile equilibrium state, which can easily lead to the failure and instability of the surrounding rock.

3. Large goaf section (Figure 2C): The maximum width of the goaf is more than 15 m. Under the action of roof pressure, the shallow surrounding rock appears to show an evident tensile failure, whereas the deep surrounding rock appears to show a serious shear failure. Furthermore, the maximum sectional area of the goaf is 135 m², and stress concentration in the surrounding rock leads to a large reduction in the strength and bearing capacity of the surrounding rock.

4. Multiple superpositions of surrounding rock stress fields with complex distributions (Figure 2A): Because of the mining of the original Shiyanhe coal mine, the area of the auxiliary shaft station is in a stress concentration zone of coal pillars with two sides of goafs, and the distributions of the goafs and abandoned roadways are unclear. This generates extremely complex, unknown, and multiply...
superpositioned stress fields in this region, thereby aggra-
vating the control difficulties regarding the main roadway
passing through the goaf.

Based on the above analysis combined with field engi-
neering experience, a “double systems” support tech-
ology for the main roadway passing through the goaf was
proposed. A high-strength “anchorage-mesh-shotcrete”
support system was adopted to form a large-scale overall
anchorage bearing structure for the goaf roof, and a double-
H-type space frame structure support system consisting of
a “reinforced concrete pillar + reinforced concrete longitu-
dinal beam + cross steel I-beam” was adopted to support
the roof and construct airtight spaces for the main roadway.
This support technology was conducive to the main road-
way passing through the goaf, thereby providing a guaran-
tee of mine safety and production.

4 | RESULTS AND DISCUSSION

4.1 | High-strength “anchorage-mesh-
shotcrete” support system for goaf roof

The fracture zone and plastic zone of the goaf roof are large,
and the rock strata cracks are extremely developed. However,
the combined support of the high-strength pretensioned anchor bolts and anchor cables can place the surrounding rock in a compression state and effectively control the deformation and failure of the surrounding rock in deep and shallow anchorage zones.\textsuperscript{42-44} In addition, a high-strength concrete spray layer can seal the shallow surrounding rock to effectively limit the arbitrary expansion of the surrounding rock fracture zone, thereby maintaining the integrity of the surrounding rock.\textsuperscript{45-57} It can be seen that the coupled actions of the high-strength pretensioned anchor bolts and anchor cables with surface protecting components such as the plate and steel mesh, along with the high-strength concrete spray layer, constitute the high-strength “anchorage-mesh-shotcrete” support system for the goaf roof, as shown in Figure 5.

4.2 Double-H-type space frame structure support system of “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam”

4.2.1 Stability bearing mechanism of reinforced concrete pillar

Calculation of compressive bearing capacity of reinforced concrete pillar

Based on the geological production conditions of the goaf and field engineering experience, reinforced concrete pillars were poured that were 500 mm × 500 mm (length × width) in size, with a row spacing of 4000 mm. The reinforcements of these pillars were composed of longitudinal HRB335 threaded steel reinforcement bars with a diameter of 20 mm and circumferential HRB335 threaded steel reinforcement bars with a diameter of 12 mm, as shown in Figure 6.

Reinforcement ratio \( \rho' \) and compressive bearing capacity \( F_u \) of the reinforced concrete pillars under axial compression are given as follows\textsuperscript{58}:

\[
\rho' = \frac{A'_s}{A},
\]

where \( A \) is the sectional area of the reinforced concrete pillar, \( A'_s \) is the sectional area of all the longitudinal compression reinforcements, \( \varphi \) is the stability coefficient, \( f_c \) is the design value of the compressive strength of the concrete under axial compression, \( f'_s \) is the design value of the compressive strength of the reinforcements, \( l_0 \) is the calculated height of the pillar, and \( b_0 \) is the size of the shorter side of the pillar cross-section.

From Figure 6, the main parameters can be determined as follows: \( A'_s = 0.002827 \text{ m}^2, A = 0.25 \text{ m}^2, b_0 = 0.5 \text{ m}, f_c = 14.3 \text{ MPa}, \) and \( f'_s = 300 \text{ MPa}. \) According to Equation (1), \( \rho' \) is calculated to be 1.13%. Because \( \rho' > 0.6\% \) and < 3\%, it meets the reinforcement requirement for a reinforced concrete pillar under normal section compression. In addition, \( l_0/b_0 \) is in the range of 8-34. Therefore, \( F_u \) is determined as follows:

\[
F_u \leq 0.9 \varphi \left( f_c A + f'_s A'_s \right), \quad (\rho' \leq 3\%) \quad (2)
\]

\[
\varphi = \begin{cases} 
0.9 \varphi \left( f_c A + f'_s A'_s \right), & (\rho' > 3\%) \\
1, & \left( \frac{l_0}{b_0} < 8 \right) \\
1.177 - 0.021 \frac{l_0}{b_0}, & \left( 8 \leq \frac{l_0}{b_0} \leq 34 \right) \\
0.87 - 0.012 \frac{l_0}{b_0}, & \left( 34 < \frac{l_0}{b_0} \leq 50 \right).
\end{cases} \quad (3)
\]
According to Equation (4), the maximum compressive bearing capacity of a reinforced concrete pillar under axial compression is 3713 kN.

To effectively control the deformation and failure of the roof strata, the bearing capacities of high-strength roof anchor cables and reinforced concrete pillars should agree with Equation (5):

$$\frac{r_1 F_u + r_2 F_2}{c} - \gamma h_1 L \geq 0,$$

where $r_1$ is the number of reinforced concrete pillars, $r_2$ is the number of anchor cables, $F_2$ is the designed bearing capacity of a single anchor cable, $c$ is the safety factor, $\gamma$ is the average unit weight of the roof rock strata, $h_1$ is the thickness of the roof rock strata, $l$ is the span of the goaf, and $L$ is the length of the goaf.

Based on the geological production conditions of the goaf and field engineering experience, the inter-row spacing of the anchor cable is set as 1.5 m × 2.0 m, and the main parameters are determined as follows: $r_1 = 16$, $r_2 = 128$, $c = 1.3$, $\gamma = 21.8$ kN/m³, $l = 15$ m, and $L = 30.5$ m. $F_2$ is calculated to be at least 296 kN, based on integrating Equations (4) and (5). At present, a high-strength pretensioned anchor cable with an elongation of 3.5% is widely used. It is composed of seven steel wires. The tensile capabilities of anchor cables and reinforced concrete pillars should agree with Equation (6):

$$\varepsilon_b = \frac{\sigma_b \beta_1}{\sigma_s + f_y},$$

where $\sigma_b$ is the stress of the tensile reinforcement when the pillar produces a balanced failure, $\beta_1$ is the ratio of the converted compression zone height of the equivalent rectangular stress block to the actual compression zone height of the section, and $f_y$ is the strength of the tensile reinforcement.

When the reinforced concrete pillar produces a balanced failure, its axial force $F_{ub}$ can be determined as follows:

$$F_{ub} = \alpha_1 f_y \varepsilon_b b h_0,$$

where $\alpha_1$ is the ratio of the stress value of the equivalent rectangular stress block of the concrete under compression to the design value of the compressive strength of the concrete under axial compression, and $h_0$ is the distance between the active point of the composite force of the tensile longitudinal reinforcement and the far edge of the section.

The reinforced concrete pillar will produce a tensile failure if $F_u \leq F_{ub}$, whereas the pillar will produce a compressive failure if $F_u > F_{ub}$, as shown in Figure 7. It can be seen from Figure 7A that the coordinates ($M$, $F_u$) of any point on the curve AD indicate that the section is in the ultimate limit state under the internal force combination of ($M$, $F_u$). For example, the pillar is in the bending state at point A, which has no compressive capacity. Point B is the dividing point for the large and small eccentric compressions of the pillar, and the pillar has the largest flexural capacity at this moment. The pillar is under axial compression at point D, which has the largest compressive capacity. In addition, the internal force combination corresponding to point F cannot force the pillar into an ultimate limit state; thus, it is a safe internal force combination. In contrast, the internal force combination corresponding to point E can force the pillar beyond the ultimate limit state, indicating that the bearing capacity of the pillar is insufficient at this moment. It can be seen from Figure 7B that the $M$–$F_u$ correlation curves ($L_1$, $L_2$, $L_3$) move outwards with an increase in the reinforcement ratio ($p'_1 < p'_2 < p'_3$) if the section shape, size, and material strength remain unchanged for a symmetrical pillar reinforcement section. This indicates that the
compressive capacity and flexural capacity of the pillar are enhanced; however, \( F_{ub} \) is not changed when a balanced failure occurs.

Based on the above analysis, combined with the geological production conditions of the goaf and field engineering experience, the main parameters are determined as follows: \( \alpha_1 = 1, \beta_1 = 0.8, f_y = 300 \text{ MPa}, h_0 = 0.42 \text{ m}, \varepsilon_b = 0.55, b_0 = 0.5 \text{ m}, \) and \( f_c = 14.3 \text{ MPa} \). According to Equation (7), the pillar is under a small eccentric compression because \( F_{ub} \) is calculated to be 1651.65 kN, that is, less than the design value for the axial force of the pillar. Figure 7A also shows that when the pillar is under a small eccentric compression, a smaller eccentricity (\( \varepsilon_0 \)) will lead to a greater axial force and stronger stability for the pillar. Therefore, the pillar can more effectively support the goaf roof. In addition, to further enhance the stability of the pillar, it should be connected to the roof when poured. Hence, four high-strength roof anchor bolts should be arranged at the four corners of the pillar for connection to the longitudinal reinforcements of the pillar.

Analysis of reducing span control mechanism of reinforced concrete pillar

The roof strata of the goaf, from bottom to top, are siltstone, mudstone, and fine sandstone. Among the rock strata, the strength and thickness of the fine sandstone are relatively high. Thus, it is a relatively stable rock stratum. In contrast, the siltstone is an unstable rock stratum because of its relatively small strength and thickness. Accordingly, the roof siltstone can be used to analyze the reducing span control mechanism of the reinforced concrete pillar.61,62 A mechanical model was constructed for the roof rock beam under the reducing span control of the reinforced concrete pillars based on the structural characteristics of the goaf roof. To simplify the model and facilitate its calculation, the following assumptions were made.

1. A rectangular mechanical model is constructed under the support of the high-strength pretensioned anchor cables and double-row reinforced concrete pillars. It is under a plane strain state, and its width is a unit width along the direction of the goaf length.
2. The two ends of the mechanical model are simplified to the clamped boundaries. Roof load \( q \) is the sum of the weights from the upper soft rock mass and the mechanical model.63-66 The bottom of the pillar is a hinge support, and it provides concentrated load \( F_u \). Considering the diffusion effects of surface protecting components such as plates, steel meshes, and steel beams on the support load of the anchor cables, support load \( p \) is regarded as having a uniform distribution, and the action range of the anchor cables corresponds to the range of the anchor cables’ inter-row spacing.

\[
R_A + R_B + pl + 2F_u = ql, \quad (10)
\]

To conveniently obtain the bending moment distribution of the mechanical model, and reveal the reducing span control mechanism of the reinforced concrete pillars, the mechanical model shown in Figure 8 can be decomposed into the mechanical models shown in Figure 9.

Because the reinforced concrete pillar has high strength and small shrinkage, and is connected to the roof when poured, the roof deflection at the action position of the pillar can be regarded as zero, and the stress of the mechanical model is symmetrical over the centerline of the main roadway. Therefore, by only considering the deflection boundary condition of the pillar on one side of the mechanical model,
the deflection equilibrium equation at the action position of the left pillar under the functions of different loads can be given as follows:

$$\omega_{c_q} + \omega_{c_p} + \omega_{c_{pq}} = 0,$$

where $\omega_{c_q}$, $\omega_{c_p}$, and $\omega_{c_{pq}}$ are the roof deflections at the action position of the left pillar under the functions of $q$, $p$, and $F_u$, respectively.

The bending moments and forces at both ends of the mechanical model under the function of the concentrated load provided by the left pillar are as follows:

$$
\begin{align*}
M_{A1} &= \frac{F_u}{l^2} \left( \frac{l}{2} + b \right)^2 \left( \frac{l}{2} - b \right), \\
M_{B1} &= \frac{F_u}{l^2} \left( \frac{l}{2} - b \right)^2 \left( \frac{l}{2} + b \right), \\
R_{A1} &= \frac{F_u}{l^2} \left( \frac{l}{2} + b \right)^2 (2l - 2b), \\
R_{B1} &= \frac{F_u}{l^2} \left( \frac{l}{2} - b \right)^2 (2l + 2b),
\end{align*}
$$

where $M_{A1}$ and $M_{B1}$ are the bending moments at both ends of the mechanical model and $R_{A1}$ and $R_{B1}$ are the forces at both ends of the mechanical model.

The relationships between the bending moments and different loads are as follows:

$$
\begin{align*}
M_{A1} + M_p &= \frac{q}{24} \left( x + \frac{l}{2} \right)^2 + \frac{(q-p)}{24} \left( x + \frac{l}{2} \right)^4 - \frac{(q-p)l}{12} \left( x + \frac{l}{2} \right)^3 \\
M_{R1} &= \frac{F_u}{l} \left( \frac{l}{2} - b \right)^2 \left( \frac{l}{2} + b \right) \left( 2l - 2b \right) \left( x + \frac{l}{2} \right)^2 \\
&\quad - \frac{l}{2} < x < -\frac{l}{2} + b,
\end{align*}
$$

Based on the above analysis, combined with the geological production conditions of the goaf and field engineering experience, the main parameters are determined as follows: $F = 240$ kN, $h = 3$ m, $l = 15$ m, $N_1 = 1.5$ m, $N_2 = 2.0$ m, and $q = 168$ kN/m. Based on the differential equation of the deflection curve and the boundary conditions of the mechanical model, the deflection equation was obtained from Equation (13). As a result, the bending moment distribution

![FIGURE 9](image_url)  
**FIGURE 9**  Decomposed mechanical models of roof rock beam under reducing span control of reinforced concrete pillars. (A) Functions of $q$ and $p$; (B) Function of $F_u$

![FIGURE 10](image_url)  
**FIGURE 10**  Bending moment distribution of mechanical model. (A) No reinforced concrete pillars support; (B) Reinforced concrete pillars support
was obtained by substituting the deflection equation into Equation (11), as shown in Figure 10.

In Figure 10A, when there are no reinforced concrete pillars providing support, the bending moment of the mechanical model exhibits a parabola-shaped distribution. The maximum bending moment of 1650 kN m is located at both ends, and the bending moment at the center is 825 kN m. In Figure 10B, when the reinforced concrete pillars support the roof, the bending moment exhibits a wave-shaped distribution, and the bending moment is significantly reduced. For example, when \( b = 2.6 \) m, a maximum bending moment of 175 kN m is observed (still located at both ends), and the bending moment at the center is 89 kN m. The reduction factors are 9.43 and 9.27, respectively, indicating that the double-row reinforced concrete pillars can effectively support the goaf roof, increase the constraint points of the roof, and reduce the roof span to further improve the roof stress state. Accordingly, it is possible to prevent roof separation instability, and even roof falls.69,70 However, with an increase in \( b \) (2.6 m \( \rightarrow \) 3.1 m \( \rightarrow \) 3.6 m \( \rightarrow \) 4.1 m), the bending moments at the center and action positions of the pillars significantly increase. Thus, the pillars can be arranged on both sides of the main roadway \( (b = 2.75 \text{ m}) \) in view of the field engineering experience.

### 4.2.2 Action mechanism of reinforced concrete longitudinal beam and cross steel I-beam

According to field observations, the roof is fluctuating and bumpy along the direction of the goaf length, and its stability is poor. Therefore, a reinforced concrete longitudinal beam is used to connect the reinforced concrete pillars along the direction of the goaf length. The reinforcement layout of the longitudinal beam is shown in Figure 11. The ultimate compressive strain of the longitudinal beam under nonuniform compression is 0.0033 if the concrete strength grade of the longitudinal beam is less than C50. The length of the longitudinal beam is 3500 mm, and its limit deflection is only 11.55 mm. This shows that the longitudinal beam can provide high resistance to the inclination instability of the pillar, to further strengthen the pillar stability once the pillar shows a small range of displacement along the direction of the goaf length. In addition, a cross steel I-beam is used to connect the pillar and longitudinal beam along the direction of the goaf width. Consequently, the reinforced concrete pillar, reinforced concrete longitudinal beam, and cross steel I-beam make up a double-H-type space frame structure that contributes to providing high support resistance for the goaf roof, enhancing the lateral pressure resistance and resistance to the deformation of the space frame structure.

### 4.2.3 Construction of double-H-type space frame structure support system of “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam”

To isolate the main roadway from the goaf and reduce the impacts of goaf ponding, and toxic and harmful gases, on the safety ventilation, haulage, and pedestrians in the main roadway, it is necessary to construct roof and side protection structures based on the reinforced concrete pillar, reinforced concrete longitudinal beam, and cross steel I-beam. A steel mesh, reinforced concrete rear panel, concrete spray layer, and loess buffer layer are set up above the cross steel I-beam in turn, to form a portable roof protection structure characterized by its simple construction, isolation ability, and shock resistance. Moreover, a brick wall with the same width as the pillar is built in the frame structure composed of the pillar and longitudinal beam, and the cement is plastered on the inner two sides of the main roadway to form side protection structures, thereby constructing a stable and airtight main roadway.

Based on the above research and field engineering experience, a double-H-type space frame structure support system consisting of a “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam” was constructed, as shown in Figure 12.

### 4.3 Support practice for main roadway passing through goaf

#### 4.3.1 Combined support scheme and construction process for main roadway passing through goaf

The criterion for the design of combined support parameters is that the support stress field generated by the anchor bolt and anchor cable supports needs to be continuous,
and an overall bearing structure can be formed. Generally speaking, the inter-row spacing of the anchor bolts is not more than 1 m, and their diameter is not <20 mm. The high-strength anchor cable needs to be anchored in the hard rock stratum to determine its length. In addition, the anchor cable can bear the weight of the rock strata in the anchorage area, and the safety factor should be considered. Finally, the anchor bolts, anchor cables, and surrounding rock form the larger range bearing structure. The design parameters of a reinforced concrete frame are mainly determined based on the roof load and its overall stability. The reinforced concrete pillars need to be connected to form an overall support system, and the safety factor should be considered. Because of the large section of goaf and difficult support, the high-strength grade C30 should be adopted for the shotcrete layer.

The combined support scheme and support parameters for the main roadway passing through the goaf were determined based on the geological production conditions of goaf #1 exposed by driving through passing chamber 1, Equations (1)-(13), and field engineering experience, as shown in Figure 13.

1. High-strength roof “anchorage-mesh-shotcrete” support: A high-strength threaded steel anchor bolt (20 mm in diameter and 2400 mm in length, with a pretightening torque of not <180 N·m) was adopted, and the inter-row spacing was 900 mm × 1000 mm. The diameter of the borehole of the anchor bolt was 28 mm. The size of the quaqua- versal steel plate was 150 mm × 150 mm × 10 mm. A roll of K2360-type resin anchorage agent and two rolls of Z2360-type resin anchorage agents were adopted for each anchor cable. The mesh size of the steel bar graticules (6 mm in diameter) was 100 mm × 100 mm. In addition, concrete was sprayed on the surrounding rock surface of the goaf roof, with a thickness of 100 mm. The strength grade of the concrete was C30.

2. Double-H-type space frame structure support: The reinforced concrete pillar and longitudinal beam were poured as a whole using C30 concrete, and their longitudinal and circumferential reinforcements were made of HRB335 threaded steel bars with diameters of 20 mm and 12 mm, respectively. The pillars were 500 mm (length) × 500 mm (width) × 1000 mm (height). The size of each pillar foundation was 700 mm (length) × 700 mm (width). The longitudinal reinforcements at the four corners of each pillar were connected to four high-strength roof anchor bolts. Moreover, the 11# cross steel I-beam was set up above the longitudinal beam. Concrete was sprayed on the floor to a thickness of 300 mm, and the strength grade of the concrete was C30. A 12# brick wall with a thickness of 500 mm was built in a 3500 mm × 3200 mm (length × height) frame formed by the reinforced concrete pillars, reinforced concrete longitudinal beam, and concrete floor. In addition, cement with a thickness of 50 mm was plastered on the inner two sides of the main roadway. The spacing of the 11# cross steel I-beam (6000 mm in length) was 800 mm, and it was fixed in place by laying brick. The
FIGURE 13 Combined support scheme for main roadway passing through goaf #1 (unit: mm). (A) Front view; (B) Side view; (C) Stereogram.
steel bar graticules (6 mm in diameter) were laid on the steel I-beam. A C30 reinforced concrete rear panel that included round steel with a diameter of 10 mm was placed on the steel bar graticules. The size of this rear panel was 800 mm x 500 mm x 50 mm. Concrete was sprayed on the rear panel with a thickness of 100 mm. After the solidification of the sprayed concrete layer, the 12\# brick wall with a height of 400 mm was built on the longitudinal beam, and a loess cushion with a thickness of not < 400 mm was laid between the two brick walls. Concrete was also sprayed under the 11\# cross steel I-beam to close the main roadway surface, until the concrete spray layer thickness was flush with the bottom of the steel I-beam. The size of the main roadway was 5000 mm x 3500 mm (width x height).

The support construction process for the main roadway was determined based on the combined support scheme for the main roadway passing through goaf #1 exposed by driving through passing chamber 1, as shown in Figure 14.

**FIGURE 14** Support construction process for main roadway passing through goaf #1
4.3.2 | Support effect

To verify the application effect of the combined support scheme consisting of the high-strength roof “anchorage-mesh-shotcrete” and the double-H-type space frame structure for the main roadway passing through goaf #1, monitoring stations (Figure 1B) were arranged to monitor the goaf roof sag, load along the anchor cables, and load along the reinforced concrete pillars. Three monitoring stations were arranged: monitoring station 1# was arranged in the middle of the goaf, and monitoring stations 2# and 3# were 12 m away from both sides of monitoring station 1#. The roof sag in the middle of the goaf was monitored at each monitoring station. The load along the anchor cable in the middle of the roof was monitored using an anchor cable dynamometer at each monitoring station. A pressure cell was installed at the top of each reinforced concrete pillar to monitor the load along the reinforced concrete pillars. Figure 15 illustrates the results from monitoring the mine pressure in the main roadway.

As shown in Figure 15, within the first 16 days, the mine pressure on the main roadway was severe. The roof sag rate was rapid, and the loads along the anchor cables and reinforced concrete pillars increased sharply. Over the next 16-30 days, the mine pressure significantly decreased. After 30 days, the roof deformation and loads along the anchor cables and reinforced concrete pillars tended to be stable. It was found that the maximum roof sag was 80 mm, and that there was no evident bed separation inside and outside the anchorage zone. The maximum loads along the anchor cable and reinforced concrete pillar were 185 kN and 2558 kN, respectively. There were no serious deformation and failure phenomena in the field (e.g., anchorage invalidation, breakage of roof anchor bolts and anchor cables, roof falls, bending damage, and peeling of the concrete spray layer). Furthermore, the brick wall remained in good condition, and the deformation and force of the supporting structure were controlled within safe ranges. The stability and sealing of the main roadway could meet the requirements for mine ventilation, pedestrians, and haulage. This indicated that the “double systems” supporting structure composed of the high-strength roof “anchorage-mesh-shotcrete” and double-H-type space frame structure consisting of the “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam” and surrounding rock could bear loads together, and an airtight main roadway space was constructed. Accordingly, the problem of surrounding rock control was effectively solved for the main roadway passing through the goaf.

5 | CONCLUSIONS

1. The roof strata of the main roadway passing through a goaf exhibit a ladder pattern of caving. The difficulty of the surrounding rock control for the main roadway passing through a goaf is aggravated by collapsed gangues un-connected to an unsupported roof, large goaf sections, and multiple superpositions of surrounding rock stress fields with complex distributions. A combined support technology consisting of roof “anchorage-mesh-shotcrete” and a double-H-type space frame structure was proposed for a main roadway passing through a goaf.

2. The double-H-type space frame structure support system is composed of a reinforced concrete pillar, reinforced concrete longitudinal beam, cross steel I-beam, steel bar graticules, reinforced concrete rear panel, concrete spray layer, loess cushion, and brick wall. It reduces span of the goaf roof and provides strong support.
of the pillar. It also enhances the shock resistance of the roof and the bending and lateral pressure resistances of the frame structure and facilitates the construction of an airtight space for the main roadway. Accordingly, it provides safety guarantees for main roadway ventilation, pedestrians, and haulage in a merger and reorganization mine.

3. After adopting the combined support scheme of the goaf roof “anchorage-mesh-shotcrete” and double-H-type space frame structure consisting of the “reinforced concrete pillar + reinforced concrete longitudinal beam + cross steel I-beam,” the crack development, bed separation, and bending subsidence of the roof were effectively controlled, and an airtight space for the main roadway was constructed, thereby realizing the common load bearing of the “double systems” supporting structure and surrounding rock. Consequently, the surrounding rock control problem for the main roadway passing through the goaf was effectively solved. Theoretical and technical bases are provided for the control of a roadway passing through a goaf under similar conditions.

Of course, the applicability of the double-H-type space frame needs to be further studied under special geological conditions such as a deep mine and fault to expand the use scope of the double-H-type space frame structure. In addition, the support parameters should be further optimized through engineering practice.

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CONFLICTS OF INTEREST
The authors declare that they have no conflict of interest.

ORCID
Dongdong Chen https://orcid.org/0000-0002-4504-8142
Qing Zhang https://orcid.org/0000-0001-7393-5649
Xiaoyu Wu https://orcid.org/0000-0001-5049-8124

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