Application of concrete-filled steel tubular columns in gob-side entry retaining under thick and hard roof stratum: A case study

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Abstract
The successful retaining of the gob-side entry under a thick and hard roof stratum is difficult because of the high pressure present and complex construction technology commonly used. To solve this problem, a new type of gob-side entry supporting system is proposed in this paper. This system is mainly composed of concrete-filled steel tubular columns (CSTCs), flexible cushion, and gob isolation structures. This new supporting system combines the high-strength support of CSTCs with the flexible support of cushion bodies and is simple to construct, enabling fast and efficient gob-side entry retaining under a thick and hard roof stratum. The range of the roof strata controlled by gob-side support structures is determined for a case study, and a calculation formula for the gob-side support resistance is established. Through theoretical and experimental research, a reasonable calculation formula for the choice of CSTC is also established. The CSTC structure ultimately selects Φ194 × 8 mm hollow steel tubes and C40 grade concrete for use in a field application, which can provide 4814 kN of supporting force. A simple on-site construction process is designed for the field application, and the time required for entry retaining per meter is only approximately 40-45 minutes. This application shows that the new technology controls the deformation of the retained entry very well; the final deformation stabilizes at 412 mm, which meets the engineering requirements.

KEYWORDS
concrete-filled steel tubular columns, gob-side entry retaining, supporting system along gob-side, thick and hard roof stratum

1 | INTRODUCTION

The technology of gob-side entry retaining allows one entry roadway of a former working face to continue to serve the next working face. Gob-side entry retaining plays an important role in reducing the volume of roadway excavation, removing the coal pillar between adjacent working faces, and increasing the recovery rate of coal resource.1,2 In the application of gob-side entry retaining technology, the artificially constructed gob-side supporting structure is a key factor. It requires enough supporting strength to sustain the weight of the upper strata and enough deformation to adapt to the movement of the roof strata. Additionally, construction of the gob-side supporting structure should be easy and not affect the normal mining
production of the working face. In recent years, many scholars have carried out considerable research on mechanical models and the structural design of gob-side supporting structures and have obtained many conclusions.3-8 The main gob-side supporting bodies currently in use include wooden stacks, densely spaced hydraulic props, gangue walls, concrete walls, and bodies filled with a high-water rapid hardening material. The construction of these above-mentioned structures on the gob-side in roadway is mainly completed by people. And these belong to a type of additional artificial supporting structure. In recent years, a new type of gob-side supporting structure was proposed by professor He et al.17,18 It formed by roof cut. By cutting down a certain width of the immediate roof, the supporting wall was formed along the gob-side in the roadway. It was used to support the upper roof and isolate the goaf. All these gob-side supporting structures have different supporting characteristics and are suitable for different conditions.

However, gob-side entry retaining engineering under a thick and hard roof stratum necessitates special requirements for the supporting body.11-14 First, the movement of the thick and hard roof stratum will produce greater a pressure, requiring that the gob-side supporting structure provide supporting resistance of at least 4000 kN/m and even up to 5000 kN/m. According to statistical analysis, one hydraulic prop can provide a supporting resistance of only approximately 300 kN, while a concrete wall 1-1.5 m thick can provide no more than 3000 kN. The low bearing capacity of these supporting bodies makes them unable to adapt to gob-side entry retaining engineering under high-stress conditions. Second, the mining intensity and efficiency are higher for the current working face. This requires that the construction of the gob-side support body should be simple and should provide entry retaining quickly. In addition, the cost of entry retaining should also be reduced as much as possible. Although the backfilled supporting body with a high-water rapid hardening material or other materials provides sufficient supporting resistance, the construction process for this supporting body is complicated, slowing entry retaining. This construction process will seriously affect the mining efficiency of the working face. Additionally, the cost of filling materials is high and negatively impacts the profit for the mining enterprises.

Based on the aforementioned analyses, increasing the supporting strength and simplify the construction process of the gob-side supporting structure are the keys to future entry retaining technology.15,16 In this paper, a new type of gob-side supporting structure consisting of “concrete-filled steel tubular columns (CSTCs) + flexible cushion” is proposed based on years of research.17,18 This structure combines the high-strength support of CSTCs with the flexibility to adapt to high pressure. Additionally, it has the advantages of quick installation, simple construction, quick entry retaining, and high cost-performance. This new structure is especially suitable for entry retaining engineering under high-stress conditions.

2 | ENGINEERING BACKGROUND

2.1 | Geological overview of retained entry

The Luxi mine is in the Jining mining area in eastern China. To increase the mining rate of the coal resources, rock entry excavation should be reduced, and the balance between mining and driving should be coordinated. The entry retaining engineering in the A02 working face was planned at the −300 m mining level. The depth of the A02 working face was approximately 280-320 m. The main coal seam mined from this working face was the No. 3, which has a thickness of 2.1 m and a dip angle of approximately 4°. The A02 working face length was 122 m, and its strike length was 778 m. Figure 1 presents the planar layout view of the A02 working face and its adjacent working faces. The gob of the A03 working face is to the west, and a 5-m-wide coal pillar was present between the A02 and A03 working faces. The A01 working face, which has not been mined, is to the east. The two main roadways of the mining district were located to the south.

The rail crossheading of the A02 working face was planned to be retained for use as the transporting crossheading of the next working face. The average length of the roadway is approximately 700 m, and the cross section is rectangular with a 3.6 m width and 2.6 m height. The primary supporting form within the entry is composed of bolts, anchor cable, wire mesh, and steel strip. The steel strip and anchor cable are used to support only the entry roof. The resin bolts used to support the roof have a spacing of 800 mm, with 900 mm between rows. The two outermost bolts have an outward offset of 15°. The rebar bolts chosen to support the roadway’s sides have a spacing of 900 mm, with 1000 mm between rows. The top and bottom row of bolts are also offset by 15°. The anchor cables are 6.5 m long and 17.8 mm in diameter and are used to support the roadway roof. The anchor cable spacing is 1600 mm, and the row distance is 2000 mm. Figure 1 shows the specific roadway supporting parameters in the study area.

2.2 | Analysis of the surrounding strata structures

According to the geological analysis of the mining district, the roof strata of the upper No. 3 coal seam are mainly siltstone, fine sandstone, and mudstone. Table 1 shows the surrounding strata structures upper the working face.

After the coal seam is mined, due to the creation of free space that allows movement, the 3.7-m-thick siltstone stratum that directly covers the coal seam will fall directly into the goaf. This layer of stratum belongs to the immediate roof category. According to the field monitoring during mining of the adjacent working face, the broken expansion coefficient of the immediate roof is approximately 1.45. Therefore, the
filling height in the goaf after immediate roof caving will be approximately 5.4 m. Then, the free space that allows movement of the 11.59-m-thick No. 2 fine sandstone will be only (2.1 + 3.7)−5.4 = 0.4 m. This is not enough free space for this stratum to cave into. Therefore, the No. 2 fine sandstone stratum will form a fractured articulated beam structure. This layer of stratum belongs to the basic roof category. For the 8.7-m-thick No. 3 siltstone stratum, it is necessary to perform a mechanical analysis to determine whether it would move with the basic roof or move independently.

Regarding two adjacent strata, the maximum curvature of the stratum subsidence $\rho_{\text{max}}$ could be utilized to judge if they will move separately or as a single strata group.\(^{19-21}\)

When $\rho_{\text{max}1} \leq \rho_{\text{max}2}$, the two strata combine into a strata group.

When $\rho_{\text{max}1} > \rho_{\text{max}2}$, the two strata move separately.

Where the $\rho_{\text{max}1}$ is the maximum subsidence curvature of the upper stratum, and $\rho_{\text{max}2}$ is the maximum subsidence curvature of the lower stratum.

According to material mechanics theory, the maximum subsidence curvature of a clamped-clamped beam can be described by the following formula:

$$\rho_{\text{max}} = \frac{\gamma L^2}{2Em^4}$$

where $\gamma$ is the volume weight of the stratum, $L$ is the hanging span of the stratum, $E$ is the elastic modulus of the stratum, and $m$ is the stratum thickness.

According to the measurement of the surrounding rock mechanics parameters and observation of the fractured length.

### Table 1

| Order | Lithology     | Thickness (m) | Depth (m) | Hardness coefficient ($f$) |
|-------|---------------|---------------|-----------|---------------------------|
| 0     | No. 3 coal seam | 2.1           | 296.39    | 1-2                       |
| 1     | Siltstone     | 3.7           | 294.29    | 4-6                       |
| 2     | Fine sandstone| 11.59         | 290.59    | 4-6                       |
| 3     | Siltstone     | 8.7           | 279.00    | /                         |
| 4     | Fine sandstone| 8.1           | 270.30    | /                         |
| 5     | Mudstone      | 2.0           | 262.20    | 3-4                       |
of the roof of the adjacent working face, the following parameters are chosen\textsuperscript{22-25}

The No. 3 siltstone stratum: \( \gamma_1 = 24.3 \text{ kN/m}^3 \), \( L_1 = 38.5 \text{ m} \), \( E_1 = 8.3 \text{ GPa} \), and \( m_1 = 8.7 \text{ m} \).

The No. 2 fine sandstone stratum: \( \gamma_2 = 25.6 \text{ kN/m}^3 \), \( L_2 = 56.2 \text{ m} \), \( E_2 = 9.6 \text{ GPa} \), and \( m_2 = 11.59 \text{ m} \).

Bringing the above parameters into Equation (1), it is found that \( \rho_{\text{max}}^1 < \rho_{\text{max}}^2 \). According to the above criteria, the No. 3 siltstone stratum and the No. 2 fine sandstone stratum will move separately. Because of the uncoordinated movement of these two strata, a certain amount of separation will occur between the two strata during the subsidence process. The No. 2 fine sandstone stratum constitutes a single basic roof structure.

In entry retaining engineering, the range of overlying strata to be controlled by the gob-side supporting body is the immediate roof and the basic roof. The upward rock strata have a low degree of fracturing and a strong bearing capacity. Their weight will be bared by the lateral coal wall and the falling gangue in the goaf. Based on the above analysis, for the entry retaining engineering of the A02 working face in the Luxi mine, the pressure exerted on the gob-side supporting structure will mainly be due to the immediate roof of 3.7-m-thick siltstone and the basic roof of 11.59-m-thick fine sandstone. According to the characteristics of the overlying strata movement after mining of the coal seams, the structural model of the overlying strata for the A02 working face entry retaining is established, as shown in Figure 2.

3 | CALCULATION OF GOB-SIDE SUPPORTING RESISTANCE

As shown in Figure 2, after the coal seam is mined, the immediate roof will cave directly into the goaf. The weight of the immediate roof suspended above the roadway will be entirely supported by the gob-side support body. In addition, due to the considerable thickness and high strength of the fine sandstone stratum of the basic roof, the pressure caused by the weight of this stratum is high. Therefore, it is not feasible to completely control the movement of the basic roof with the supporting body. To effectively reduce the resistance of the gob-side supporting body and the supporting cost, it is necessary to allow a certain amount of subsidence of the basic roof stratum, causing the basic roof to break above the solid coal. And the articulated rock beam structure forms after the basic roof breaks\textsuperscript{26,27} Finally, the pressure of the rock block \( B \) of the basic roof is supported by the solid coal wall, gob-side supporting body, and caved gangue in the goaf\textsuperscript{19,28}. In this structure mode, the early supporting resistance of the gob-side supporting body can reduce the speed of the rock block movement only within a certain range and cannot stop the movement of the basic roof.

Before rock block \( B \) contacts the gangue in the goaf, it is required that the gob-side supporting body should have a sufficient compressibility to adapt to the rotation and subsidence of the basic roof. Additionally, the gob-side supporting body should also have a certain early supporting resistance to shorten the period of violent movement of the basic roof. After the rock block \( B \) contacts the gangue in the goaf, the gob-side supporting body should have enough supporting resistance and strength to control the stability of rock block \( B \)\textsuperscript{29,30}\n
Based on the above analysis, the gob-side supporting body should control the weight of the fully suspended immediate roof and the movement stability of the rock block \( B \) that forms after the basic roof breaks, as shown in Figure 2.

A mechanical model is established based on the final position after the basic roof comes into contact with the gangue in the goaf, and the calculation of the gob-side supporting resistance is performed, as shown in Figure 3.

First, the following simplifying assumptions are made in the mechanical model.

(a) After the basic roof breaks, because of its obvious separation from the overlying strata, it is believed that the basic rock beam is not affected by the weight of the overlying strata.
The shear stresses among the immediate roof, basic roof, and overlying strata are not considered during the analysis. (b) The basic roof is rotated toward the goaf side with the elastic-plastic interface of the coal wall as the axis of rotation. (c) Basic roof rock block $B$ and rock blocks $A$ and $C$ are hinged at $B_1$ and $B_2$, respectively. However, the lateral compressive forces and shear forces created due to the basic roof rock blocks $A$ and $C$ acting on rock block $B$ are not considered.15,17

After the basic roof reaches the final stable position, the weight and pressure of the thick and hard basic roof block $B$ and the immediate roof are jointly supported by the coal wall, gob-side supporting body, and caved gangue in the goaf.

### 3.1 Immediate roof pressure analysis

Based on the above analysis, the immediate roof will cave in the goaf after the coal seam is mined. By entry retaining, the weight of the immediate roof suspended above the roadway will be totally supported by the gob-side supporting body. The weight of the immediate roof, $F_5$, can be calculated according to the following formula:

$$F_5 = \gamma_z m_z b$$  \hspace{1cm} (2)

where $\gamma_z$ is the volume weight of the immediate roof, kN/m$^3$; $m_z$ is the thickness of the immediate roof, m; and $b$ is the retaining width of the entry, m.

### 3.2 Pressure analysis of the basic roof block $B$

For basic roof block $B$, static balance and moment balance analyses are performed. Based on the static equilibrium conditions in the vertical direction, $\Sigma F_y = 0$,

$$F_1 + F_2 + F_3 - F_4 = 0$$  \hspace{1cm} (3)

where $F_1$ is the supporting force provided by the physical coal wall to rock block $B$; $F_2$ is the supporting force provided by the gob-side supporting body to rock block $B$; $F_3$ is the supporting force provided by the caved gangue in the goaf to rock block $B$; and $F_4$ is the weight of rock block $B$.

Based on the moment balance of point $B_1$, $\Sigma M_{B_1} = 0$,

$$\frac{1}{2} F_1 a + F_2 (a + b) + F_3 L - \frac{1}{2} F_4 L = 0$$  \hspace{1cm} (4)

where $a$ is the plastic zone width in the coal wall, and $L$ is the length of rock block $B$, that is, the periodic fracture step length of the basic roof.

The load of the solid coal in the plastic zone in the roof is simplified to a linear distribution, as shown in Figure 3. The load intensity at the fracture position of the basic roof and the coal wall in the entry are $q_1$ and $q_2$, respectively. Then, force $F_1$ of the solid coal on the roof can be calculated as.

$$F_1 = \frac{1}{2} a(q_1 + q_2)$$  \hspace{1cm} (5)

The stress of the weight of the basic roof block $B$, $F_4$, can be calculated according to the following formula:

$$F_4 = \gamma_E m_E L$$  \hspace{1cm} (6)

where $\gamma_E$ and $m_E$ are the volume weight and thickness of the basic roof block $B$, respectively.

Solving Equations (3)-(6), the supporting resistance $F_2$ provided by the gob-side supporting body to the basic roof block $B$ is obtained:

$$F_2 = \frac{2L^2 \gamma_E m_E - (2aL - a^2)(q_1 + q_2)}{4(L - a - b)}$$  \hspace{1cm} (7)

Combining Equations (2) and (7), the overall supporting force $F$ provided by the gob-side supporting body is.

$$F = F_2 + F_5 = \frac{2L^2 \gamma_E m_E - (2aL - a^2)(q_1 + q_2)}{4(L - a - b)} + \gamma_z m_z b$$  \hspace{1cm} (8)

### 4 CSTC BEARING CAPACITY ANALYSES

Concrete-filled steel tubes (CSTCs) have been widely utilized in modern building and bridge engineering because it...
is both very strong and very stable. The internal concrete is in a triaxial compressive state due to the constraints of the tubular steel shell. Therefore, this core of concrete has a high compressive strength. Additionally, both the internal concrete and the tubular steel shell bear the axial pressure, thereby enhancing the geometric stability and avoiding the premature local buckling damage of the steel tube wall. In addition, the CSTC structure has a cylindrical shape, and this form demonstrates a higher bending stiffness and is not easily distorted; therefore, it is more structurally stable. The CSTC structure is presented in Figure 4. The CSTC exhibits outstanding advantages as the main gob-side supporting body in entry retaining engineering. CSTCs have a higher bearing capacity and structural stability compared with traditional wooden stacks, gangue walls, dense hydraulic props, etc. Compared with the emerging gob-side filling body that contains concrete and other high-water rapid hardening materials, the CSTC also has the advantages of low cost, simple construction, fast entry retaining, and so on. Therefore, in a high-stress environment, the CSTC is an ideal gob-side supporting structure in efficient entry retaining engineering.

4.1 | Theoretical calculation

There are many calculation standards and rules governing the bearing capacity of the CSTC, for example, rules ACI (2005) and AISC (2005) in the United States, AIJ (1997) in Japan, and BS5400 (2005) in England. In China, Professor Cai proposed that the ultimate bearing capacity of a CSTC can be calculated according to the limit equilibrium theory. This type of theory holds that the ultimate bearing capacity of a CSTC can be calculated according to the limit equilibrium theory under axial compression. Therefore, the ultimate bearing capacity of a CSTC can be calculated according to the mechanical equilibrium conditions when the structure is in the limit equilibrium state. It is not necessary to determine the constitutive relation of the material, regardless of the loading history and deformation process.

According to above analysis, the ultimate bearing capacity of a CSTC can be calculated using the following formula:

\[ N_0 = A_c f_c (1 + 2\theta) \]  \hspace{1cm} (9)

\[ N_0 = A_c f_c \left(1 + \sqrt{\theta} + 1.1\theta \right) \]  \hspace{1cm} (10)

where \( N_0 \) is the ultimate bearing capacity of a CSTC; \( A_c \) is the cross-sectional area of the core concrete; and \( f_c \) is the compressive strength of the core concrete, in MPa, as shown in Figure 4. In addition, a hoop index \( \theta \) is introduced to express the confinement degree of the steel tube on the core concrete. Here, \( \theta = A_s f_s / A_c f_c \), where \( A_s \) is the cross-sectional area of the steel tube and \( f_s \) is the ultimate yield strength of the steel, in MPa. \( D_s \) and \( D_c \) are the outside diameter of the steel pipe and the diameter of the core concrete, respectively; \( t \) is the thickness of the steel pipe.

Assuming that the values of \( N_0 \) in Equations (1) and (2) are equal, \( \theta \) was calculated to be 1.235. Thus, the following statements can be made:

When \( \theta \leq 1.235 \), the ultimate bearing capacity of a CSTC is calculated according to Equation (9).

When \( \theta > 1.235 \), the ultimate bearing capacity of a CSTC is calculated according to Equation (10).

4.2 | Experimental study

To test the ultimate bearing capacity of a CSTC and establish the corresponding relationship between the theoretical result and measured values, the compressive strengths of different types of CSTCs were tested in a structural mechanics laboratory.

4.2.1 | Experimental method

The experiments were executed in a 500 t hydraulic press in the structural laboratory of Shandong Jianzhu University. The experimental equipment and specimen arrangement are shown in Figure 5. A dial indicator and a steel tape are arranged at each diagonal position of the press plates. The dial indicator is used to measure the displacement of the tested specimen during the elastic deformation stage; the steel tape is used to measure the large deformation of the specimen during the plastic deformation stage. The loaded pressure value is read directly from the dashboard of the pressure console. The graded slow loading mode is adopted in the pressurization process. In the initial stage of the experiment, the pressure is loaded in 200 kN increments. After the pressure exceeds 1000 kN, it is increased in 100 kN increments. The loading time for each pressure stage is approximately 3-5 minutes. Then, the pressure and the axial deformation
of the test specimen are recorded. The overall experimental time required for each specimen is generally approximately 2 hours.

4.2.2 | The testing specimens

During the CSTC mechanical property experiments, the ultimate bearing capacity of several types of CSTCs formed by combining steel tubes of various thicknesses and diameters with different grades of core concrete were tested. According to the industry standard in China, GB/8162-2008, for the use of a seamless pipe for structure, the selected steel pipe material was 20# low-carbon steel, which has a yield strength of 235 MPa and a tensile strength of 410 MPa. The selected pipe diameters were Φ168, Φ194, and Φ219 mm. The selected wall thicknesses of the steel pipe were 8 and 10 mm. The core concrete strength was required to meet those of the C30 and C40 grades (which have uniaxial compressive strengths of 30 and 40 MPa, respectively). The CSTC-specific structural parameters are presented in Table 2.

4.3 | Experimental results

In the mechanical tests, the tested CSTCs demonstrated a high bearing capacity. In addition, in the process of axial compression, the specimens clearly underwent stages of elastic deformation and plastic flow deformation. The maximum load of the plastic flow stage is defined as the corresponding ultimate bearing strength of the CSTC. According to experimental tests, the ultimate bearing capacity results for various types of CSTCs are listed in Table 3.

According to Equations (8) and (9), the ultimate bearing capacities of the tested CSTCs are calculated. The theoretical calculation results are also listed in Table 3. Following a comparative analysis of the data, the histograms comparing the theoretical and measured values of the ultimate bearing capacity of each CSTC are shown in Figure 6.

The ultimate bearing capacity of a CSTC obtained by the formula following the limit equilibrium theory is very close to the corresponding ultimate bearing capacity obtained from the experiment. The tested values are slightly higher than the theoretical values, and the comprehensive error ratio is 1%-4.2%. Therefore, it is appropriate to use the above theoretical calculation formula to analyze the bearing capacity of a CSTC. However, an adjustment factor is required. According to the comparative analysis, the average error ratio of 2.52% is taken as the adjustment factor. Thus, Equations (9) and (10) become.

\[
N_0 = 1.025A_f (1 + 2\theta) \\
N_0 = 1.025A_f (1 + \sqrt{\theta} + 1.1\theta)
\]

These two equations can be used to determine the bearing capacity of a CSTC utilized in entry retaining engineering.

5 | CASE STUDY

5.1 | The design of the A02 working face entry retaining system

5.1.1 | The overall scheme

According to the geological and geotechnical conditions of the A02 working face in the Luxi coal mine, a specific technical scheme for gob-side entry retaining is designed. The CSTC is adopted as the main gob-side supporting structure to control the roof strata movement and provide a sufficiently high supporting strength. A certain amount of space is reserved between the column and the roof, and a wooden wedge is placed in this space as a flexible cushion layer. Diamond-shaped wire mesh, rubber cloth, and bags filled with gangue are used as the isolation structures to insulate the harmful gasses and gangues in the caving goaf. As the working face advances, a row of roof-control anchor cables will be installed near the side of the coal wall and will hang the immediate roof on the hard and stable overlying stratum. This measure could ensure the integrity of the surrounding rocks in the roadway and provide sufficient time and space for the installation of the CSTC. Hydraulic props are used in the roadway as a temporary enhanced supporting measure before the CSTC is fully functional. The overall supporting scheme of entry retaining is shown in Figure 7.

5.1.2 | The selection of CSTC type

According to the study of the gob-side supporting resistance in the third part of this paper, the gob-side supporting
resistance can be calculated after obtaining the characteristic parameters of the rock surrounding the roadway. The bulk density of the immediate roof (siltstone stratum) $\rho_z$ is taken to be 24.3 kN/m$^3$, the immediate roof thickness $m_z$ is taken to be 3.7 m, the bulk density of the basic roof (fine sandstone stratum) $\rho_E$ is taken to be 25.6 kN/m$^3$, and the basic roof thickness $m_E$ is taken to be 11.6 m. The width of the retained entry $b$ is 3.6 m. According to the observation data of the ground pressure collected during mining of the adjacent A03 working face, the periodic fracture length of the rock beam of the basic roof is approximately 20 m. The plastic zone width of the solid coal in front of the working face is approximately 6 m (the basic roof fractures are positioned 6 m in front of the coal wall). It is assumed that $L = 20$ m and that $a = 6$ m. Based on the field monitoring, the load is $q_1 = 100$ kN/m at the fractures in the solid coal, and the load is $q_2 = 240$ kN/m at the coal wall. These parameters are substituted into Equation (8) to calculate the minimum supporting resistance provided by the CSTC gob-side supporting body: The minimum supporting resistance is approximately 4367 kN.

In general, the CSTC is considered a short column when its ratio of length to diameter is $L/D \leq 4$. The previous theoretical and experimental studies on the ultimate bearing capacity of a CSTC are based on short columns. However, the CSTCs used for the gob-side supporting body are clearly categorized as long columns. According to the research, with the increase in the length-diameter ratio of the CSTC, the actual bearing capacity of the long columns will be reduced compared with that of the short columns due to the buckling effect. The reduction factor of the bearing capacity can be expressed by the following empirical formula:

$$\varphi = 1 - 0.115 \sqrt{l/d - 4}$$  \hspace{1cm} (13)

Therefore, the actual bearing capacity of the CSTC used as the gob-side supporting body can be calculated following formula (14):

$$N_a = \varphi \cdot N_0$$  \hspace{1cm} (14)
where \( N_u \) is the actual bearing capacity of the long column.

According to the analysis of the retained entry size of the A02 working face and the movement law of the roof, the net height of the roadway is 2.6 m, and the free space of the basic roof is at least 0.4 m. Therefore, the length of the CSTC is designed to be 2.2 m. According to Equations (11) and (12), the bearing capacity of the selected short CSTC composed of a \( \Phi299 \times 8 \) mm steel tube and C40 grade concrete can reach 6102 kN. The reduction factor of the long column, \( \varphi \), is 0.789 according to Equation (13). Substituting the above parameters into Equation (14), it can be determined that the actual bearing capacity of the long CSTC used for the gob-side supporting body is \( N_u = 4814 \) kN > 4367 kN. This bearing capacity meets the demand for the support resistance.

Therefore, the specific parameters of the CSTC selected for the gob-side supporting structure of the A02 working face are determined as follows: The material selected for the seamless steel pipe is 20# low-carbon steel, which has a yield strength of 235 MPa; the outer diameter of the steel pipe is 299 mm; the wall thickness is 8 mm; the length of the CSTC is 2.2 m; and the internal concrete strength grade is C40.

5.1.3 | Design of gob-side supporting parameters

The layout of the CSTC

To achieve the optimal gob-side supporting effect and effectively reduce the cost of the support, the distance between the centers of adjacent columns in the direction of the roadway axis is set at 600 mm. Based on the bearing capacity of the selected CSTC, this arrangement can provide 2.23 MPa of supporting strength for the roof strata. The gaps between adjacent columns are filled with gangue bags to prevent the caved gangue in the goaf from rolling into the roadway space. The design structure and layout of the CSTCs are shown in Figure 8. According to the earlier analysis, the free movement space of the overlying basic roof is approximately 0.4 m after the immediate roof caves. Therefore, the design length of the CSTC is 2.2 m and is not connected to the roof. The space between the column and the roof is filled with a wooden wedge, which acts as a flexible cushion layer. The main function of the cushion layer is to reduce the movement speed of the basic roof as it sinks.

The parameters of the roof-control anchor cables

To prevent the immediate roof above the roadway near the gob area from falling as mining continues and to reserve a sufficient time and space for the installation of the CSTC, a row of roof-control anchor cables is installed near the side of the coal wall in front of the working face. The distance between the coal wall and the anchor cable is approximately 100 mm, as shown in Figure 9. The distance between two adjacent anchor cables is 1250 mm, and every two adjacent anchor cables are connected by a 1.5-m-long I-beam. The length of each anchor cable is 6500 mm.

The assisted reinforcement supporting measures

After the gob-side supporting body is installed, the roof pressure during the early stage is mainly supported by the flexible cushion layer. The CSTC provides a high-strength bearing capacity only after the wooden wedge is compacted. Therefore, in order to prevent major deformation of the roadway, hydraulic props are installed within the roadway to reinforce the support. These hydraulic props are withdrawn after the wooden wedge is compacted, and CSTC is under pressure. According to the entry size, three hydraulic props are arranged per row, and the distance between adjacent props is 800 mm. The three hydraulic props are connected by an articulated steel beam. The distance between adjacent rows
of props is 1200 mm. The layout of the hydraulic props is shown in Figure 9.

5.2 | The on-site construction process

The order of the main steps executed during the construction process of the CSTC gob-side entry retaining engineering design is shown in Figure 10.

In the above construction steps, the anchor cables, wire mesh, rubber cloth, gangue bags, and hydraulic props are constructed using conventional construction techniques. The key steps include the construction of the empty CSTC and the concrete perfusion. The installation of the empty CSTC follows the advancement of the working surface. After the installation location and direction were determined, the first step of the installation was the treatment of the entry floor. This step is mainly to ensure that the empty column was placed on a relatively flat bottom plate. The second step was erection of the empty column. Due to the heavy weight of the empty steel pipe, this step needs to be completed by 2-3 workers using the installation tools. The installed empty column needs to be perpendicular to the roof and floor plate. After the empty column was erected, the flexible cushion was installed between it and the roof plate. The installation time required for each empty column is approximately 20 minutes. Centralized concrete perfusion is carried out after approximately 6-8 empty columns have been installed. The equipment required to concrete perfusion includes blender, filling pump, and delivery pipeline. The grouting hole was located in the lower part of the empty column; therefore, the concrete slurry was poured into the empty steel pipe from the bottom to the top when perfusion, just as shown in Figure 12. This ensures that the empty steel pipe was filled with concrete slurry. The grouting time for each column is approximately 10 minutes. The grouting construction process is shown in Figures 11 and 12.

The filling materials, blender, and filling pump were placed in the crossheading in front of the working surface. These devices continue to move forward as the working surface is mined. The delivery pipeline consists of a steel pipe and a delivery hose, which transports the filling slurry into each empty CSTC. The proportion of components in the concrete slurry is as follows: cement:fine aggregate:coarse aggregate:water reducer:water at 1:1.2:2.3:0.02:0.42. The cement consists of ordinary Portland cement and fast hard sulphoaluminate cement. The fast hard sulphoaluminate cement
accounts for 20% of the total cement component. The coarse aggregate is gravel with particle sizes of 15~25 mm. In addition, the fine aggregate is high-quality river sand.

5.3 | Field surveys

To verify the effect of the gob-side entry retaining engineering design that utilizes the CSTC structure, field monitoring of the deformation of the reserved roadway was carried out during implementation of the project. The metrics recorded during monitoring included the movement of the roof-floor and the left-right sides of the roadway. One monitoring point was positioned every 10 m from the first installed column, and a total of 10 monitoring points were used. The monitoring range was approximately 100 m, and the monitoring duration was approximately 1 month. A statistical analysis was performed on the obtained monitoring data; the resultant curve of the deformation of the retained entry with distance to the working face is shown in Figure 13.

According to the analysis of the monitoring results, the cycle break length of the basic roof is maintained at approximately 20 m. The movement of the basic roof exhibits a slow sinking stage before fracturing; during this stage, the basic roof sinks <50 mm. Additionally, the flexible cushion layer (wooden wedge) plays a major role during this stage, continuously undergoing compressive deformation. After the basic roof fractures, it exhibits a drastic sinking stage. The deformation of the retained roadway reached 395 mm in 5 days. During this stage, the wooden wedge is completely compressed, and the CSTCs begin to play a major role. When the basic roof beam is in contact with the caved gangue in the goaf, the CSTCs achieve their maximum bearing capacity, and the roadway approximately stops deforming. The final deformation stabilizes at approximately 412 mm, which is compatible with the designed pressure-relief space. This final deformation meets the requirements of use. The CSTCs did not show any obvious bending deformation and maintained good structural stability. The CSTCs controlled the movement and deformation of the overburden rock strata effectively. The final effect of this gob-side entry retaining engineering design is very good, as shown in Figure 14.

6 | DISCUSSIONS

The keys to the success of gob-side entry retaining technology are the choice of material and performance of the gob-side supporting body. The main advantages of using the “CSTCs + flexible cushion layer” as the gob-side supporting body are as follows:

6.1 | High supporting cost-performance ratio

Compared with traditional gob-side supporting structures such as gangue walls and dense hydraulic props, a CSTC has a higher bearing capacity. According to theoretical and experimental research, the ultimate bearing capacity of gangue walls and dense hydraulic props is only 200-300 kN. The ultimate bearing capacity of a CSTC of at least Φ194 × 8 mm exceeds 3200 kN. Moreover, the supporting resistance of the column can be quickly made available, and it is more suitable for gob-side entry retaining engineering under high-stress conditions. Compared with a gob-side supporting body
constructed of concrete-filled material and high-water rapid hardening material, the CSTC gob-side supporting body has a lower manufacturing cost. According to this investigation, for an equal supporting resistance, the cost of a CSTC is approximately 20%-30% that of the required high-water rapid hardening material. Therefore, a CSTC has a higher supporting cost-performance ratio.

6.2 Simple construction process and fast entry retaining

The new type of gob-side supporting structure proposed in this paper is mainly composed of CSTCs. The production of the hollow steel tubes can be completed on the ground. The construction process within the coal mine consists of only the installation of empty columns and the pouring of concrete slurry. According to the application in the Luxi mine, the average time for the installation and grouting of a CSTC is approximately 10-15 minutes. Therefore, the installation speed of CSTCs can keep pace with the mining speed at the working surface. In addition, installation of CSTCs does not have any effect on the production of the working face. In contrast, the construction of a gob-side supporting body composed of a concrete-filled wall and high-water rapid hardening materials is complex and requires adding another filling system to the mining system under the coal mine. The speed of constructing a 1- to 2-m-filled wall is often approximately 4-5 h/m, which is slower than the mining speed of the working surface. In this case, the working face will sometimes have to stop production to wait for the construction of the gob-side supporting body. This will have a great impact on the production efficiency of the working surface. And the gob-side entry retaining technology formed by roof cutting also contains many process steps such as blasting precracking, roof maintenance and strengthening support in the roadway. Therefore, this technology will also affect the production efficiency of the working surface.

In summary, the new type of gob-side entry retaining technology that utilizes the CSTC structure can not only provide a higher supporting resistance but also effectively reduce the cost of the support, simplify the construction process, and greatly accelerate the speed of entry retaining. This is an efficient gob-side entry retaining technology with a very broad application prospect.

7 CONCLUSIONS

To achieve efficient gob-side entry retaining under a thick and hard roof stratum, this paper proposes a new type of gob-side supporting system based on the CSTC. In this system, the CSTC is the main gob-side supporting structure that provides high supporting resistance. A flexible cushion layer fills the space between the CSTC and the roof and is able to effectively release the pressure from the basic roof. Gangue bags, wire mesh and rubber cloth are used as isolation measures for the goaf. The roof-control anchor cables and hydraulic props within the entry are used as auxiliary support measures.

Taking the A02 working face of the Luxi coal mine as a case study, the range of roof strata that should be controlled...
by the gob-side supporting structure was determined. A mechanical model of the gob-side entry retaining under a thick and hard roof stratum was established. In addition, a reasonable calculation formula was obtained for the gob-side supporting resistance. The supporting resistance provided by the proposed gob-side supporting body was at least 4367 kN at the A02 working face.

The ultimate bearing capacity of a CSTC was studied theoretically and experimentally to establish the correlations between the measured results and theoretical calculations results. A reasonable calculation formula for the selection of CSTC was obtained. Via calculation, the final parameters of the CSTC selected for the gob-side supporting structure of the A02 working face were determined. The seamless steel pipe’s outer diameter is 299 mm, its wall thickness is 8 mm, and the internal filled concrete strength grade is C40. This type of CSTC can provide 4814 kN of supporting resistance.

An efficient field construction process was designed for the new gob-side entry retaining technology. According to the field application, the entry was well retained. The final deformation of the roadway was stable at approximately 412 mm, which can meet the normal use requirements of the next working surface.

The innovative gob-side entry retaining technology based on the CSTC structure is more suitable for entry retaining engineering under high-stress conditions and clearly exhibits the advantages of a high supporting resistance, low supporting cost, and simple construction process.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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REFERENCES

1. Zhang N, Han CL, Kan JG, Zheng XG. Theory and practice of surrounding rock control for pillarless gob-side entry retaining. *J Chin Coal Soc*. 2014;39(8):1635-1641.
2. He MC, Gao YB, Yang J, Gong WL. An innovative approach for gob-side entry retaining in thick coal seam longwall mining. *Energies*. 2017;10(11):1785.
3. Yavuz H. An estimation method for cover pressure re-establishment distance and pressure distribution in the goaf of longwall coal mines. *Int J Rock Mech Min Sci*. 2004;41(2):193-205.
4. Esterhuizen E, Mark C, Murphy MM. Numerical model calibration for simulating coal pillars, gob and overburden response. Proceedings-the 29th International Conference on Ground Control in Mining. Morgantown, WV: 46-57.
5. Han CL, Zhang N, Li BY, Si GY, Zheng XG. Pressure relief and structure stability mechanism of hard roof for gob-side entry retaining. *J Cent South Univ*. 2015;22:4445-4455.
6. Zhang ZZ, Bai JB, Chen Y, Yan S. An innovative approach for gob-side entry retaining in highly gassy fully-mechanized longwall top-coal caving. *Int J Rock Mech Min Sci*. 2015;80:1-11.
7. Li XH, Ju MH, Yao QL, Zhou J, Chong ZH. Numerical investigation of the effect of the location of critical rock block fracture on crack evolution in a gob-side filling wall. *Rock Mech Rock Eng*. 2016;49:1041-1058.
8. Ning JG, Wang J, Bu TT, Hu SC, Liu XS. An innovative support structure for gob-side entry retention in steep coal seam mining. *Minerals*. 2017;7(5):75.
9. Hu JZ, He MC, Wang J, Ma ZM, Wang YJ, Zhang XY. Key parameters of roof cutting of gob-side entry retaining in a deep inclined thick coal seam with hard roof. *Energies*. 2019;12(5):1-19.
10. Yang J, He MC, Cao C. Design principles and key technologies of gob side entry retaining by roof pre-fracturing. *Tunn Undergr Sp Tech*. 2019;90:309-318.
11. Jirankova E. Utilisation of surface subsidence measurements in assessing failures of rigid strata overlying extracted coal seams. *Int J Rock Mech Min Sci*. 2012;53:113-119.
12. Tan YL, Yu FH, Ning JG, Zhao TB. Design and construction of entry retaining wall along a gob side under hard roof stratum. *Int J Rock Mech Min Sci*. 2015;77:115-121.
13. Yang DW, Ma ZG, Qi FZ, et al. Optimization study on roof break direction of gob-side entry retaining by roof break and filling in thick-layer soft rock layer. *Geomech Eng*. 2017;13(2):195-215.
14. Huang BX, Liu JW, Zhang Q. The reasonable breaking location of overhanging hard roof for directional hydraulic fracturing to control strong strata behaviors of gob-side entry. *Int J Rock Mech Min Sci*. 2018;103:1-11.
15. Bai JB, Zhou HQ, Hou CJ, Tu ZX, Yue DZ. Development of support technology beside roadway in goaf-side entry retaining for next sublevel. *J Chin Univ Min Tech*. 2004;33(2):183-186.
16. Bai J-B, Shen W-L, Guo G-L, Wang X-Y, Yu Y. Roof deformation, failure characteristics, and preventive techniques of gob-side entry driving heading adjacent to the advancing working face. *Rock Mech Rock Eng*. 2015;48:2447-2458.
17. Huang WP, Gao YF, Wen ZJ, Gao L. Technology of gob-side entry retaining using concrete-filled steel tubular column as roadside supporting. *J Chin Univ Min Tech*. 2015;44(4):604-611.
18. Wang J, Gao YF, He XS, et al. The analysis of roadside supporting parameters and the support technology in the concrete filled steel tubular column in goaf-side entry retaining. *J Min Safe Eng*. 2015;32(6):943-949.
19. Song ZQ. *Practical Ground Pressure Control*. Xuzhou: China University of Mining and Technology Press; 1988.
20. Wang J, Ning J, Jiang L, Jiang J-Q, Bu T. Structural characteristics of strata overlying of a fully mechanized longwall face: a case study. *J South Afr Inst Min Metall*. 2018;118:1195-1204.
21. Huang WP, Li C, Zhang LW, Yuan Q, Zheng YS, Liu Y. In situ identification of water-permeable fractured zone in overlying composite strata. *Int J Rock Mech Min Sci*. 2018;105:85-97.
22. Huang WP, Xing WB, Chen SJ, Liu Y, Wu K. Experimental study on sedimentary Rock's dynamic characteristics under creep state using a new type of testing equipment. *Adv Mater Sci Eng*. 2017;2017:1-13.
23. Liu XS, Tan YL, Ning JG, Lu YW, Gu QH. Mechanical properties and damage constitutive model of coal in coal-rock combined body. *Int J Rock Mech Min Sci*. 2018;110:140-150.
24. Guo WY, Tan YL, Yu FH, et al. Mechanical behavior of rock-coal-rock specimens with different coal thicknesses. *Geomech Eng*. 2018;15(4):1017-1027.
25. Feng F, Li XB, Rostami J, Peng DX, Li DY, Du K. Numerical investigation of hard rock strength and fracturing under polyaxial compression based on Mogi-Coulomb failure criterion. *Int J Geomech*. 2019;9(4):04019005.
26. Feng F, Chen SJ, Li DY, Hu ST, Huang WP, Li B. Analysis of fractures of a hard rock specimen via unloading of central hole with different sectional shapes. *Energy Sci Eng*. 2019. https://doi.org/10.1002/ESE3.432
27. Jiang BY, Gu ST, Wang LG, Zhang GC, Li WS. Strainburst process of marble in tunnel-excavation-induced stress path considering intermediate principal stress. *J Cent South Univ*. 2019;26(4):984-999.
28. Singh G, Singh UK. Prediction of caving behavior of strata and optimum rating of hydraulic powered support for longwall workings. *Int J Rock Mech Min Sci*. 2010;47:1-16.
29. Li ZL, Dou LM, Cai W, Wang GF, DingYL, Kong Y. Roadway stagger layout for effective control of gob-side rock bursts in the longwall mining of a thick coal seam. *Rock Mech Rock Eng*. 2016;49:621-629.
30. Wen ZJ, Xing ER, Shi SS, Jiang YJ. Overlying strata structural modeling and support applicability analysis for large mining-height stopes. *J Loss Prevent Proc*. 2019;57:94-100.
31. Ellobby E, Ghazy MF. Experimental investigation of eccentrically loaded fiber reinforced concrete-filled stainless steel tubular columns. *J Constr Steel Res*. 2012;76:167-176.
32. Kwan A, Dong CX, Ho J. Axial and lateral stress-strain model for concrete-filled steel tubes. *J Construct Steel Res*. 2016;122:421-433.
33. Huang WP, Yuan Q, Tan YL, et al. An innovative support technology employing a concrete-filled steel tubular structure for a 1000-m-deep roadway in a high in situ stress field. *Tunn Undergr Sp Tech*. 2018;73:26-36.
34. Cai SH. *Modern Steel Tube Confined Concrete Structures* (revised edition). Beijing: China Communications Press; 2007.
35. Tan YL, Gu QH, Ning JG, Liu XS, Jia ZC, Huang DM. Uniaxial compression behavior of cement mortar and its damage-constitutive model based on energy theory. *Materials*. 2019;12:1309.
36. Fang K, Zhao TB, Zhang YB, Qiu Y, Zhou JH. Rock cone penetration test under lateral confining pressure. *Int J Rock Mech Min Sci*. 2019;119:149-155.
37. Goode CD, Kuranovas A, Kvedaras AK. Buckling of slender composite concrete-filled columns. *J Civ Eng Manag*. 2010;16(2):230-237.
38. Yin YC, Zhao TB, Zhang YB, et al. An innovative method for placement of gangue backfilling material in steep underground coal mines. *Minerals*. 2019;9:107.

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