Geomechanics and Engineering, *Vol. 15, No. 6 (2018) 1173-1182*
DOI: https://doi.org/10.12989/gae.2018.15.6.1173

Coordinated supporting method of gob-side entry retaining in coal mines and a case study with hard roof

X.S. Liu[1,2a], J.G. Ning[*1], Y.L. Tan[1b], Q. Xu[1c] and D.Y. Fan[2d]

[1]*State Key Laboratory of Mining Disaster Prevention and Control Co-founded by Shandong Province and the Ministry of Science and Technology, Shandong University of Science and Technology, Qingdao, China*
[2]*State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou 221116, China*

(Received December 11, 2017, Revised February 19, 2018, Accepted February 27, 2018)

Abstract. The coal wall, gob-side backfill, and gangues in goaf, constitute the support system for Gob-side entry retaining (GER) in coal mines. Reasonably allocating and utilizing their bearing capacities are key scientific and technical issues for the safety and economic benefits of the GER technology. At first, a mechanical model of GER was established and a governing equation for coordinated bearing of the coal-backfill-gangue support system was derived to reveal the coordinated bearing mechanism. Then, considering the bearing characteristics of the coal wall, gob-side backfill and gangues in goaf, their quantitative design methods were proposed, respectively. Next, taking the No. 2201 haulage roadway serving the No. 7 coal seam in Jiangjiawan Mine, China, as an example, the design calculations showed that the strains of both the coal wall and gob-side backfill were larger than their allowable strains and the rotational angle of the lateral main roof was larger than its allowable rotational angle. Finally, flexible-rigid composite supporting technology and roof cutting technology were designed and used. In situ investigations showed that the deformation and failure of surrounding rocks were well controlled and both the coal wall and gob-side backfill remained stable. Taking the coal wall, gob-side backfill and gangues in goaf as a whole system, this research takes full consideration of their bearing properties and provides a quantitative basis for design of the support system.

Keywords: gob-side entry retaining; coordinated bearing; coal-backfill-gangue; support design; flexible-rigid composite support; roof cutting

1. Introduction

Gob-side entry retaining (GER) technology is to retain the former mining roadway as a return airway for the next coal face by constructing an artificial wall along the goaf to support it. It is a pillar-less mining technology that is widely used in the coal mines in China: it can improve the recovery rate of coal resources, eliminate the stress concentration caused by coal pillars, solve the problem of gas accumulation at coal face corners, and achieve good economic and social benefits (Li *et al*. 2000, Monjezi *et al*. 2011, Tan *et al*. 2015a, Zhang *et al*. 2012, Nie *et al*. 2018, Zhou *et al*. 2018). However, due to the influences of twice mining actions and longer service time, both the supporting difficulty and cost of GER are much larger than these of an ordinary roadway (Ying *et al*. 2016, Zhang *et al*. 2015, Chen *et al*. 2016a, Feng *et al*. 2017, Zhao *et al*. 2017b, Zhao *et al*. 2018).

Many researchers have contributed to the support theory, design and material of GER technology. In terms of the movement of the gob-side lateral roof, Sun *et al.* (1992) and Huang and sun (1997) established a roof-breakage model and divided the roof movement process into three stages: early stage, transitional stage and later stage. The demands imposed upon the support system at different stages were studied (Tan *et al*. 2015a, Jiang *et al.* 2011, Liu *et al*. 2013, Ma *et al*. 2011, Zhang *et al*. 2015, Chen *et al*. 2016b, Yang *et al*. 2017). In terms of the support materials (Bai *et al.* 2004, Cheng *et al*. 2012, Tan *et al*. 2015b, Liu *et al*. 2016, Tan *et al*. 2018, Wu *et al.* 2018), it changed from deck wood, prop, strip pack, and concrete block to paste material, high water-content material, and ultra-high water-content material. The support resistance, its increasing rate of operations, and the contractibility of gob-side backfill improved greatly, while the labour intensity was reduced. In terms of the gob-side supporting technology, to improve the self-bearing capacity of surrounding rocks, Hua *et al*. (2005), and Chen *et al.* (2012) suggested using high-tensile pre-stressed bolts and cables to strengthen the support structure in the roadway and at the gob-side. Tan *et al*. (2015a), Ning *et al*. (2017a), Huang *et al.* (2018) and Wang *et al*. (2011a) proposed to transfer most of the roof weights to the gangues in goaf by using flexible-rigid composite supporting technology, which can effectively protect the integrity of gob-side backfill and reduce overall cost. These

∗Corresponding author, Professor
E-mail: njglxh@126.com
[a]Ph.D.
E-mail: xuesheng1134@163.com
[b]Professor
E-mail: yunliangtan@163.com
[c]M.Sc. Student
E-mail: 1101119112@qq.com
[d]M.Sc. Student
E-mail: 2460791279@qq.com

http://www.techno-press.org/?journal=gae&subpage=7 ISSN: 2005-307X (Print), 2092-6219 (Online)

researches effectively ensured the safe of GER in shallow buried and thin or medium-thick coal seams with soft or medium-hard roof, and lay foundation for application of the GER technology (Fan *et al*. 2014, Kang *et al.* 2015, Tan *et al.* 2017, Yang *et al.* 2016, Ning *et al.* 2017a, Zhang *et al.* 2017).

However, field practices showed that the GER technology was not always safe and economic. Especially in conditions with large occurrence depth, hard roof, or large mining height, many accidents such as roof collapse and wall caving have occurred in the gob-side roadway in China, resulting in high risk of underground personnel and great economic loss (Wang *et al.* 2015, Chen *et al*. 2016b, Ning *et al.* 2017b). In-situ investigations on the accidences in GER showed a common phenomenon that either the coal wall or gob-side backfill, or both of them was destroyed due to overloading while the other support part(s) was far away from its(their) ultimate bearing capacity (Zhang *et al*. 2015, Wang *et al*. 2011b, Hua *et al*. 2018, Xue *et al*. 2013, Zhang *et al.* 2006, Jiang *et al.* 2017). The reason may not only lie in the fact that the weights of overlying strata are much larger and the lateral roof strata move more violent, but also be that the loadings are not reasonably allocated on the three parts of the supporting system. In fact, the coal wall, gob-side backfill, and gangues in goaf should bear the weights of overlying strata as a whole in these conditions, and only one or two of them alone cannot support the roof strata and ensure enough section size effectively. Owing to the significant differences of these three supporting parts in bearing performances, only by reasonably regulating the roof weights loading thereon while taking full advantage of the bearing capacity of gangues in goaf, can the GER technology achieve its best effect.

Bearing this in mind, this article first established a coordinated bearing model for the support system of GER and derived a coordinated bearing equation. Then, design methods for coordinated bearing capacities of the coal wall, gob-side backfill, and gangues in goaf were proposed. Finally, in situ investigation of the No. 2201 haulage roadway in Jiangjiawan Mine, China, was presented to demonstrate the procedures and validity of the designed methods.

2. Mechanical rationale

2.1 Mechanical model

Underground excavations in coal mines showed that the lateral immediate roof usually falls with the mining of the coal face and has a certain hanging length when the roof is hard (Jiang *et al.* 2016, Singh 2015, Schumacher and Kim 2014). The lateral main roof fractures when reaching its ultimate span, and then rotates along the fracture line (usually above the coal seam). The overlying soft strata cannot form a steady structure and subside with the main roof. When GER technology is adopted, the coal wall, gob-side backfill, and gangues in the goaf bear the weights of the immediate roof, main roof, and overlying soft strata to maintain stability of the surrounding rocks of GER. As shown in Fig. 1, the immediate roof needing support is the

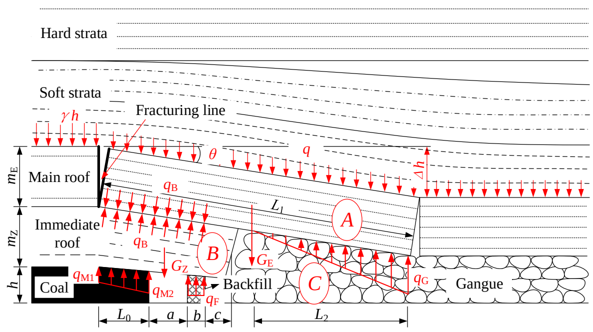


Fig. 1 The structure model and forces on surrounding rocks of GER (Tan *et al.* 2015a, Ning *et al*. 2018)

un-caved part outside the fracture line of main roof (rock beam *B*), and it is borne by the coal wall and gob-side backfill. The main roof needing support is the fractured part (rock beam *A*), and its weight and that of the overlying soft strata are borne by the immediate roof and gangues in goaf. And the part bore by the immediate roof is then transfer to the coal wall and gob-side backfill.

Taking rock beams *A* and *B* as the research objects, they are loaded by the overlying soft strata and borne by the lower coal wall, gob-side backfill, and gangues in goaf. Approximately, the weights of the overlying soft strata can be expressed as a uniform load, q; the supporting role of the coal wall can be expressed by a trapezoidal distributed load, ranging from q_{M1} to q_{M2}; the supporting role of gob-side backfill can be expressed by a uniform load, q_F; and the supporting role of gangues C can be expressed by a triangular distributed load, ranging from 0 to q_G, as shown in Fig. 1. Apparently, the acting length of the uniform load, q, is the length of rock beam A, L_1; the acting length of the trapezoidal distributed load, q_{M1} to q_{M2}, is the distance from the fracture line to the edge of coal wall, L_0; and the uniform load, q_F, acts over is its own length, b.

With the rotational angle of lateral main roof increasing, the right edge of rock beam *A* touches the gangues in goaf first and the contacting point moves left gradually, so the bearing length of the gangues increases correspondingly; however, it would not be longer than the hanging length of lateral main roof. If we suppose that the separation between lateral main roof and gangues in goaf before rotation of the lateral main roof is h_m, then the bearing length of the gangues after rotation by θ can be expressed as

$$L_2 = \begin{cases} 0 & \theta \le \arcsin \dfrac{h_m}{L_1} \\ \sqrt{L_1^2 - h_m^2} - \dfrac{h_m}{\tan\theta} & \theta > \arcsin \dfrac{h_m}{L_1} \end{cases} \tag{1}$$

where $h_m = h - (K_m - 1)m_Z$.

With rotation of lateral main roof, rock beams *A* and *B* will reach a force equilibrium state under loading of the overlying soft strata and supporting of the coal wall, gob-side backfill, and gangues in goaf. So we have

$$\frac{q_{M1} + q_{M2}}{2} L_0 + q_F b + \frac{q_G}{2} L_2 - qL_1 \cos\theta = G_E + G_Z \tag{2}$$

If we suppose that the largest deformation of the coal wall is Δh_M, the mean deformation of gob-side backfill is Δh_F and the largest deformation of gangues is Δh_G when the rotation angle of rock beam *A* is θ, the largest strain of the coal wall, ε_{M2}, the mean strain of gob-side backfill, ε_F, and the largest compression ratio of gangues *C*, K_G, can be respectively expressed as

$$\varepsilon_{M2} = \varepsilon_{M1} + \frac{\Delta h_M}{h_1}, \quad \varepsilon_F = \frac{\Delta h_F}{h_2}, \quad K_G = \frac{\Delta h_G}{K_m \cdot m_Z} \tag{3}$$

In fact, the coal wall, gob-side backfill, and gangues *C* enjoy a certain deformation compatibility during rotation of the rock beam *A*. According to the deformation-compatibility relationship, we have

$$\tan\theta = \frac{\Delta h_M}{L_0} = \frac{\Delta h_F}{L_0 + a + b/2} = \frac{\Delta h_G + h_m}{L_1 \cos\theta} \tag{4}$$

Supposing that the bearing functions of the coal wall, gob-side backfill and gangues are as follows

$$q_M = f(\varepsilon_M), \quad q_F = \varphi(\varepsilon_F), \quad q_G = g(K_G) \tag{5}$$

By substituting Eqs. (3)-(5) into Eq. (2), the governing equation for coordinated bearing capacity of the support system of GER can be derived as

$$\begin{aligned} &\frac{L_0}{2}\left(f(\varepsilon_{M1}) + f\left(\varepsilon_{M1} + \frac{L_0\tan\theta}{h_1}\right)\right) + b\varphi\left(\frac{(L_0 + a + 0.5b)\tan\theta}{h_2}\right) \\ &+ \frac{L_2}{2} g\left(\frac{L_1\sin\theta - h + (K_m - 1)m_Z}{K_m m_Z}\right) - qL_1\cos\theta = G_E + G_Z \end{aligned} \tag{6}$$

2.2 Coordinated bearing mechanism

In certain geological conditions, the weight of rock beam *B*, G_Z, the weight of rock beam *A*, G_E, the uniform load from the overlying soft strata, *q*, the distance from the fracture line to edge of the coal wall, L_0, the length of rock beam *A*, L_1, the width of the roadway, *a*, the width of gob-side backfill, *b*, the thickness of the lateral immediate roof, m_Z, the mining height, *h*, the thickness of the coal seam, h_1, the height of gob-side backfill, h_2, the initial bulking coefficient of gangues in goaf, K_m, the virgin strain of the coal seam, ε_{M1}, the bearing function of the coal wall, *f*, the bearing function of the gob-side backfill, φ, and the bearing function of the gangues, *g*, can all be obtained from laboratory tests and field monitoring. According to Eqs. (1) and (6), we can calculate the rotational angle when the lateral roof reaches a force equilibrium state and obtain the corresponding deformations and forces of the coal wall, gob-side backfill, and gangues, respectively.

During the movement of the lateral roof, the coal wall, gob-side backfill, and gangues have to bear loads together. One, or two, of them cannot control the deformation of the surrounding rocks effectively, which may lead to failure of the GER. The gangues in goaf exist in a granular state and would not lose structural stability. Researches showed that their bearing capacity increases exponentially with the strain (Zhao *et al*. 2017a; Wang *et al*. 2018; Komurlu *et al*. 2016). However, the bearing capacities and allowable deformations of the coal wall and gob-side backfill are limited. The coal wall and gob-side backfill will fail when the rotational angle, θ, is too large, resulting in failure of GER. Therefore, the gangues in goaf should bear the weights of the main roof and overlying soft strata as much as possible, and the bearing capacities and allowable deformations of the coal wall and gob-side backfill should be used as key design indices.

During the supporting design process of a GER project, if we use the bearing capacities of the coal wall and gob-side backfill as design indices, the larger the rotational angle of rock beam *A* is when it reaches a force equilibrium state, the larger the weights of lateral roof and overlying soft strata are supported by gangues in goaf. In other word, the weight supported by the coal wall and gob-side backfill will be small, which is a good situation. However, if we use the allowable deformations of the coal wall and gob-side backfill as design indices, the larger the rotational angle of rock beam *A* is, the larger the deformations of the coal wall and gob-side backfill will be, which is an adverse situation. Therefore, the larger rotational angle demands more of the allowable deformations of the coal wall and gob-side backfill, while the smaller rotational angle demands more of the bearing capacities.

If the surrounding rocks of GER deform too large so as to cause failure to maintain stability, improving the bearing capacities and increasing the allowable deformations of the coal wall, gob-side backfill, and gangues would be beneficial according to Eq. (6). Many measures are available to that end: e.g. changing the support parameters of bolts and cables in the coal wall can improve its bearing capacity; changing the filling materials or using flexible-rigid composite supporting technology can improve the bearing capacity and increase the allowable deformation of gob-side backfill; or gob-side roof cutting can decrease the weights of lateral roof and overlying soft strata. By adopting different measures, the weights of lateral roof and overlying strata can be reasonably distributed on the coal wall, gob-side backfill and gangues. In this way, the bearing capacity advantage of the gangues can be fully mobilised, and safety and economic benefits accrue.

Moreover, limited by the transport and ventilation functions, the section shrinkage of a gob-side roadway should not be more than 25% (Tan et al. 2011). So the allowable rotational angle of rock beam *A* can be expressed as

$$[\theta] = \arctan\frac{0.25h_3}{L_0 + a} \tag{7}$$

3. Design method for the support system

3.1 Gob-side backfill

For a certain coal face, the weights of rock beams *A* and *B* and their overlying soft strata are all known. If the bearing properties of the coal wall and gangues in goaf are fixed and known, then that of the gob-side backfill can be designed according to the following four steps.

Step one: substituting Eq. (1) into Eq. (6) and making the second term in Eq. (6) on the left equals zero, we then

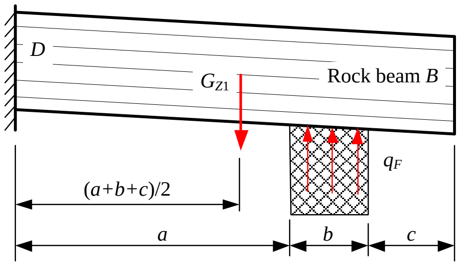


Fig. 2 Cantilever beam structure of rock beam A

obtain a function of the rotational angle, θ. As the support force of gob-side backfill is neglected in this function, the rotational angle calculated from this function is the largest rotational angle, θ_{max}. By substituting the roadway width, a, the distance from the fracture line to the edge of coal wall, L_0, and some other parameters into Eq. (7), we can obtain the allowable rotational angle of rock beam A in this condition, $[\theta]$.

Step two: comparing the largest rotational angle, θ_{max}, and the allowable rotational angle, $[\theta]$: if θ_{max} is not larger than $[\theta]$, the rotational angle can satisfy the demand of the allowable rotational angle of rock beam A without supporting of gob-side backfill. In this condition, the role of gob-side backfill is to avoid fracturing of rock beam B, and its bearing capacity should be designed following Step three (below). If θ_{max} is larger than $[\theta]$, the gob-side backfill has to bear some weights of rock beam A and its overlying soft strata to satisfy the demands of the allowable rotational angle. The design method is shown in Step four.

Step three: the rock beam B can be seen as a cantilever beam clamped by the rock beam A and the lower coal seam, and it is supported by gob-side backfill, as shown in Fig. 2. The largest bending stress on the cantilever beam can be calculated by Eq. (8), and the stability criterion is such that the largest bending stress is smaller than the allowable bending stress, $[\sigma]$. Therefore, the bearing capacity of gob-side backfill can be expressed by Eq. (9) when its strain, ε_F, equals $\frac{L_0+a+0.5b}{h_2}\tan\theta_{max}$.

$$\sigma = \frac{M_D}{W_D} \tag{8}$$

where $M_D = \frac{m_Z\gamma_Z(a+b+c)^2 - q_F b(a+0.5b)^2}{2}$, $W_D = \frac{m_Z^2}{6}$

$$q_F > \frac{3m_Z\gamma_Z(a+b+c)^2 - m_Z^2[\sigma]}{3b(a+0.5b)^2} \tag{9}$$

Step four: substituting the allowable rotational angle of rock beam A into Eq. (6), we can obtain the bearing capacity of gob-side backfill, which can be expressed by the following formula when its strain, ε_F, equals $\frac{L_0+a+0.5b}{h_2}\tan[\theta]$.

$$\begin{aligned} q_F \cdot b \geqslant\; & qL_1\cos[\theta] - \frac{L_0}{2}\left(f(\varepsilon_{M1}) + f\left(\varepsilon_{M1} + \frac{L_0\tan[\theta]}{h_1}\right)\right) \\ & - \frac{L_2}{2}g\left(\frac{L_1\sin[\theta] - h + (K_m-1)m_Z}{K_m m_Z}\right) + G_E + G_Z \end{aligned} \tag{10}$$

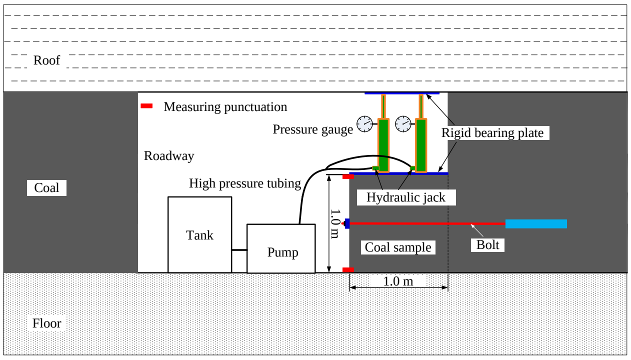


Fig. 3 Schematic diagram of an in situ testing system for the bearing property of coal wall

The bearing capacity of gob-side backfill is positively correlated with its cost, and the cost increases dramatically once the bearing capacity exceeds a certain value. Therefore, when the required bearing capacity of gob-side backfill, calculated by Eq. (10), is too large, we can reduce this demand to save cost by sharing some weights of rock beam A and overlying soft strata to the coal wall and gangues in goaf.

3.2 Coal wall

The stability of coal wall and its bearing capacity play a significant role in the stability of surrounding rocks of GER: improving the bearing capacity of coal wall is an effective measure to reduce the deformation and improve the stability of surrounding rocks. If the coal wall deforms significantly or the bearing capacity of gob-side backfill calculated by Eq. (10) is too large, measures such as bolting and grouting can be taken to improve the bearing capacity of coal wall (Gao *et al*. 2014, Lee 2016, Liu *et al*. 2018a, Bai *et al*. 2012, Wang *et al*. 2016), which are also beneficial to reducing filling costs.

For a certain coal face, if the bearing properties of gob-side backfill and gangues in goaf are fixed and known, the support parameters of coal wall can be obtained from the following three steps:

Step one: calculating the allowable rotational angle of rock beam A, $[\theta]$, according to Eq. (7).

Step two: substituting the allowable rotational angle, $[\theta]$, into Eqs. (1) and (6), then the bearing capacity of coal wall at a strain of $\varepsilon_{M1} + \frac{L_0\tan[\theta]}{h_1}$ can be expressed by Eq. (11).

$$\begin{aligned} (q_{M2}+q_{M1}) \cdot L_0 \geqslant & -L_2 g\left(\frac{L_1\sin[\theta] - h + (K_m-1)m_Z}{K_m m_Z}\right) \\ & -2b\varphi\left(\frac{(L_0+a+0.5b)\tan[\theta]}{h_2}\right) + 2(G_E+G_Z+qL_1\cos[\theta]) \end{aligned} \tag{11}$$

Step three: an independently developed testing system was used to conduct in situ tests to obtain the bearing capacities of coal wall with different support parameters. The testing system comprised a loading system and a monitoring system: the loading system included a hydraulic jack, pump, tank, high-pressure tubing, a rigid bearing plate, etc., and the monitoring system consisted of a pressure gauge, total station, measuring punctuations, etc., as shown in Fig. 3. The stress and strain of coal wall can be calculated using Eqs. (12)-(13).

$$\sigma_M = \frac{n\pi d_S^2 p_S}{4S_C} \tag{12}$$

$$\varepsilon_M = \frac{\Delta h_C}{h_C} \tag{13}$$

A testing unit measured 1.0 m in width, 1.0 m in length, and 1.0 m in height. We can draw the bearing property curves of coal wall with different support parameters from the tests, and obtain the optimal support parameter that satisfy the Eq. (11).

3.3 Gangues in goaf

When the calculated bearing capacities of gob-side backfill and coal wall are too large, the construction of GER becomes difficult, or the filling costs are too large. In this condition, we can cut the hanging part of rock beam *B* and a certain thickness of rock beam *A* to reduce the weights needed to be supported. This gob-side roof cutting measure can also increase the initial thickness of gangues in goaf, which can reduce the potential movement space of rock beam *A*. In this way, the demand for bearing capacities of coal wall and gob-side backfill can be reduced.

For a certain coal face, if the bearing capacities of coal wall and gob-side backfill are known, the design procedures of gob-side roof cutting are as follows:

Step one: calculating the allowable rotational angle of rock beam *A*, $[\theta]$, according to Eq. (7).

Step two: substituting the allowable rotational angle, $[\theta]$, into Eq. (6) and making the hanging length of rock beam *B*, *c*, equal zero, then the largest deformation of gangues in goaf, Δh_G, and the corresponding bearing capacity, q_G, can be expressed by Eqs. (14)-(15), respectively.

$$\Delta h_G = L_1 \sin[\theta] - h + (K_m - 1) m_Z \tag{14}$$

$$\begin{aligned} q_G \cdot \frac{L_2}{2} \geqslant G_E + G_Z - L_0\left(f(\varepsilon_{M1}) + f\left(\varepsilon_{M2} + \frac{L_0 \tan[\theta]}{h_1}\right)\right) \\ - b\varphi\left(\frac{(L_0 + a + 0.5b)\tan[\theta]}{h_2}\right) + qL_1\cos[\theta] \end{aligned} \tag{15}$$

Step three: a mould was manufactured to test the bearing performance of gangues in goaf. It was made of stainless steel and measured 300 mm × 300 mm × 300 mm. The side displacements of gangues are limited during the loading process, and the loading device and mould are shown in Fig. 4. The variation of bearing force of gangues with compression ratio can be obtained from a loading test, from which we can ensure the compression ratio, K_C, that satisfying the bearing capacity calculated by Eq. (15). Combined with Eq. (14), the cutting thickness of rock beam *A*, m_C, can be derived as

$$m_C = \frac{L_1 \sin[\theta] - h + (K_m - 1) m_Z}{K_m \cdot K_C} - m_Z \tag{16}$$

Step four: if $m_C \leq 0$, we should only cut the hanging part

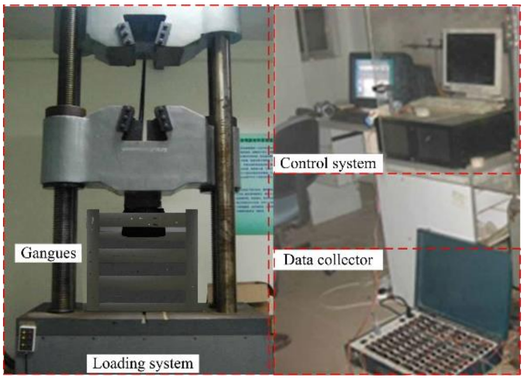


Fig. 4 The loading device and mould used to test gangues in goaf

of rock beam *B*. However, if $m_C > 0$, we need to cut rock beam *A* with a thickness of m_C.

It should be noted that the deformations of coal wall and gob-side backfill should be smaller than their allowable deformations throughout to ensure stability. Moreover, the bearing capacities of coal wall, gob-side backfill, and gangues should be compatibly configured to coordinate the loads exerted on them in a reasonable manner. Only in this way, are the optimal safety and economic benefits reaped.

4. Case study

4.1 Field overview

A typical operational trial was performed in No. 2201 haulage roadway serving the No. 7 coal seam in Jiangjiawan Mine, China. The average burial depth of the coal seam is about 216 m, and it is characterised by simple structure and stable occurrence. In detail, its thickness ranges from 1.43 to 2.43 m, with a dip angle of 3 to 5°. The immediate roof is sandy mudstone and fine sandstone with a thickness of 5.04 m, and its density and initial concentrated swell coefficient, K_m, are 2608 kg/m^3 and 1.36, respectively. The main roof is siltstone with a thickness of 14.7 m, and its density is 2725 kg/m^3. It was hard with the uniaxial compressive strength ranging from 80 MPa to 150 MPa. There are 9.32 m thick gritstone and 8.69 m thick sandy mudstone above the main roof. These strata are soft, of low strength, and move with the main roof (for further details, see Table 1).

No. 7201 coal face was the first mining face of the No. 301 panel that was mined in the No. 7 coal seam: fully mechanised coal mining methods were adopted. The average strike and slope lengths were 730 m and 126.5 m, respectively, and the coal face layout was shown in Fig. 5. The roadways were excavated along the roof and were supported by bolts and cables. The No. 2201 haulage roadway was 4.5 m in width and 2.6 m in height, and the No. 5201 tail way was 3.5 m in width and 2.2 m in height. The No. 2201 haulage roadway was preserved as a tail-way for the next coal face by using GER technology. The proportions of paste filling materials were listed in Table 2. The coal wall was supported using bolts with the following parameters: bolt diameter 18 mm, bolt length 1.7 m, and

Table 1 Lithological description of the roof strata

Sequence	Appellation	Thickness (m)	Symbol	Description
1	Medium-grained sandstone	11.19		Light grey, contain feldspar and quartz chips, medium hard
2	Sandy mudstone	8.69		Grey, pelitic texture Hardness $3 \le f \le 4$
3	Gritstone	9.32		Dark grey, contain some pyrites, sub-horizontal bedded
4	Siltstone	14.7		Light grey, densification, vertical stratification
5	Sandy mudstone, Fine sandstone	5.04		Mainly sandy mudstone, contains some coal cinders in the bottom
6	No. 7-2 seam	2.09		Dark, weak glass lustre

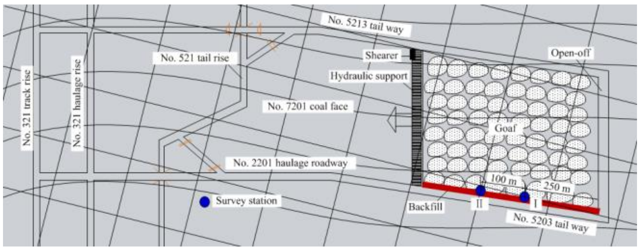


Fig. 5 Layout of the coal faces

Table 2 The proportions of paste filling materials

Amount of each kind of material in the bulk fill (kg/m^3)							Granularity (mm)
Water	Cement	Coal ash	Gangue particles	River sand	Early strength agent	Water reducing agent	
243.9	298.5	80.1	154.7	413.1	5.1	5.8	5 to 10

Fig. 6 GER with the original support parameters

bolt intervals of 800 mm horizontally and 1000 mm vertically. During retention of the No. 2201 haulage roadway, the roof subsided significantly, and macro-cracks appeared in both the coal wall and gob-side backfill, as shown in Fig. 6. Therefore, the roadway was reinforced and repaired many times to maintain the stability of the surrounding rocks: this not only wasted lots of manpower and money, but also seriously affected the mining safety and efficiency.

4.2 Optimisation design

Field observations found that the virgin strain of the coal seam, ε_{M1}, and the virgin stress, q_{M1}, were 0.0085 and 1.2 MPa, respectively. After the coal face was mined, the hanging length of the immediate roof (rock beam B), c, was

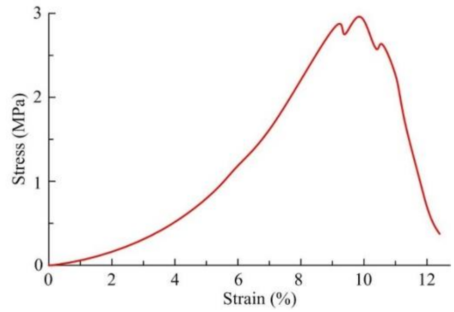


Fig. 7 Loading test curve: gob-side backfill sample

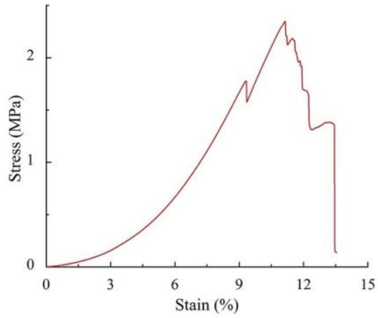
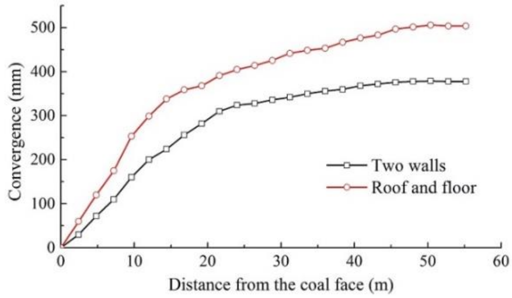
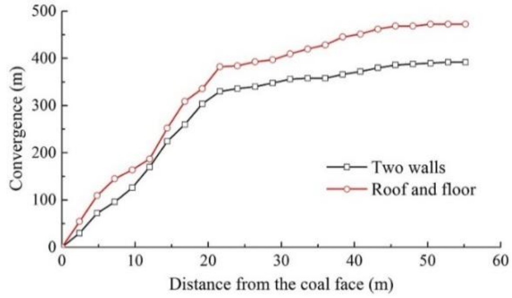


Fig. 8 Stress-strain curve: bolted coal seam



(a) Station I



(b) Station II

Fig. 10 Measured relative convergences of surrounding rocks with optimized support parameters

Fig. 11 The GER works with optimal support parameters

3.2 m, the fracture length of the lateral main roof (rock beam *A*), L_1, was 16.8 m, and the distance from the fracture line to edge of the coal wall, L_0, was 2.4 m.

According to the proportions of paste filling material in Table 2, specimens measuring 100 mm ×100 mm × 100 mm were made in the laboratory. The specimens were put into a curing chamber with the temperature of 25 ℃ and the humidity of 90% for 28 days. After that, they were subjected to uniaxial loading by using the MTS 815 electro-hydraulic servo rock mechanical test system. The stress-strain curve was obtained, as shown in Fig. 7. The bearing capacity of bolted coal was tested by using the in situ testing system developed in Subsection 3.2, and the test result was shown in Fig. 8. The bearing performance of gangues in goaf was tested using the loading device and mould introduced in Subsection 3.3, and the test curve was shown in Fig. 9.

Substituting the above parameters into Eqs. (1) and (6), the rotational angle of the lateral main roof when it reaches a force equilibrium state, θ_1, was obtained using trial and error method, and it was 5.98°. In this condition, the strains of both the bolted coal wall and the gob-side backfill were larger than their allowable strains, which explained why the coal wall and gob-side backfill failed during field trials (see Fig. 6). To ensure that the roadway can satisfy the demands of transportation and ventilation, the allowable rotational angle of the lateral main roof, $[\theta]$, was calculated according to Eq. (7). It was 4.71°, smaller than the rotational angle, θ_1. Therefore, measures must be taken to reduce the rotational angle, θ_1, to be no larger than the allowable angle, $[\theta]$. According to Section 3, technologies such as gob-side roof cutting and flexible-rigid composite supporting can be used to optimise the support system.

Making the rotational angle of the lateral main roof in Eqs. (3) and (4) equal the allowable angle, 4.71°, then the largest strain of the coal wall, ε_{M2}, is 0.1031 and the strain of the gob-side backfill, ε_F, is 0.1609. Figs 7-8 show that the bolted coal wall can meet this deformational duty while the gob-side backfill cannot: more measures must be taken to improve the allowable strain if the gob-side backfill. Some literatures suggested using flexible-rigid composite supporting technology to improve the deformation capacity of the gob-side backfill (Wang *et al*. 2011a; Liu *et al*. 2018b; Tan *et al*. 2015a; Yang *et al*. 2017). In this design, we chose the paste filling material in Table 2 and the “Youle II” filling material (manufactured by Uroica Mining Safety Engineering Co., Ltd, China) as the rigid and flexible materials, respectively. The thickness of the flexible material, h_4, can be calculated using the following formula.

$$h_4 = \frac{(L_0 + a + 0.5b)\tan[\theta] - 2.09[\varepsilon_F]}{K_{F2}}$$

The largest compression ratio of the “Youle II” filling material was 0.8, so its thickness was calculated to be 0.6443. According to Eqs. (14)-(15), the largest deformation of gangues in goaf was 1.1032 m and the corresponding supporting force, q_G, should not be less than 1.819 MPa. Fig. 9 showed that the compression ratio of gangues in goaf should not be less than 0.283 to meet this demand of supporting force. Substituting the parameters into Eq. (16) showed that the cutting thickness of the lateral main roof, m_C, should not be less than 2.87 m.

5. Conclusions

The aim of this study was to ensure the safety of GER in coal mines, by designing the bearing capacities of the coal wall, gob-side backfill, and gangues in goaf. By comparison with previous studies, this work contains at least three original aspects: (1) the governing equation for coordinated bearing capacity of the coal-backfill-gangue system was obtained based on a structural model of GER, which revealed the coordinated bearing mechanism of the coal wall, gob-side backfill, and gangues in goaf. (2) Methods for artificial adjustment measures and their quantitative design were put forward to achieve coordinated bearing of the coal-backfill-gangue system to the benefit of both safety and cost. (3) A laboratory test method for the bearing performance of gangues in goaf and an in situ testing system and method for the bearing capacity of bolted coal were developed.

Field practices in the No. 2201 haulage roadway serving the No. 7 coal seam in Jiangjiawan Mine showed that the rotational angle of the lateral main roof when it reached a stable state was larger than the allowable rotational angle. Both the strains of the coal wall and gob-side backfill were larger than their allowable strains. Calculations showed that both the flexible-rigid composite supporting technology and roof cutting technology should be used in this GER. The optimised support parameters were as follows: the 0.6443 m thick “Youle II” material was used as the flexible filling material; the cutting thickness of the main roof was larger than 2.87 m. The field monitoring results demonstrated that the deformation of the surrounding rocks was effectively controlled and no macro-cracks appeared on the coal wall and gob-side backfill. The largest convergence between the roof and floor was 488 mm, and that between the two walls was 385 mm.

This article focuses on the coordinated bearing mechanism of the coal-backfill-gangue support system and its design method. During the derivation, some assumptions and approximations were made to simply the calculations. It is necessary to conduct more in situ investigations under different geological conditions to improve the model in the future.

Acknowledgements

This study was supported by National Key R&D Program of China (no. 2018YFC0604703), National Natural Science Foundation of China (nos. 51474137, 51574154), Shandong Province Natural Science Fund (nos. ZR2018QEE002, ZR2016EEB23), Research Fund of The State Key Laboratory of Coal Resources and safe Mining, CUMT (no. SKLCRSM18KF014), Science and Technology Program of Shandong Province University (no.J15LH02), and Tai’shan Scholar Engineering Construction Fund of Shandong Province of China.

References

Bai, J.B., Zhou, H.Q., Hou, C.J., Tu, X.Z. and Yue, D.Z. (2004), "Development of support technology beside roadway in goaf-side entry retaining for next sublevel", *J. China Univ. Min. Tech.*, **33**(2), 183-186.

Bai, Q.S., Xia, Y.Y., Liu, X.X. and Yang, Z.H. (2012), "Mining roadway support technology based on rheological analysis in Malin coalmine", *Energy Procedia*, **16**, 1129-1134.

Chen, M., Yang, S.Q., Zhang, Y.C. and Zang, C.W. (2016a), "Analysis of the failure mechanism and support technology for the Dongtan deep coal roadway", *Geomech. Eng.*, **11**(3), 401-420.

Chen, S.J., Wang, H.L., Wang, H.Y., Guo, W.J. and Li, X.S. (2016b), "Strip Coal Pillar Design Based on Estimated Surface Subsidence in Eastern China", *Rock Mech. Rock Eng.*, **49**(9), 3829-3838.

Chen, Y., Bai, J.B., Zhu, T.L., Yan, S., Zhao, S.H. and Li, X.C. (2012), "Mechanisms of roadside support in gob-side entry retaining and its application", *Rock Soil Mech.*, **33**(5), 1427-1432.

Chen, Y.L., Meng, Q.B., Xu, G., Wu, H.S. and Zhang, G.M. (2016b), "Bolt-grouting combined support technology in deep soft rock roadway", *J. Min. Sci. Technol.*, **26**(5), 777-785.

Cheng, Y.H., Jiang, F.X., Lin, J.K., Chen, Q.H., Zhang, D. and Feng, F.S. (2012), "Experimental study on gob-side entry retaining by roadside flexible packing under hard roof", *J. Min. Safety Eng.*, **29**(6), 757-761.

Du, J.P. and Meng, X.R. (2009), *Mining Science*, China University of Mining and Technology Press, Xuzhou, China.

Fan, K.G. Liang, H.G. Ma, C.S. and Zang, C.W. (2014), "Non-harmonious deformation controlling of gob-side entry in thin coal seam under dynamic pressure", *J. Rock Mech. Geotech. Eng.*, **6**(3), 269-274.

Feng, X., Zhang, N., He, F., Yang, S. and Zheng, X. (2017), "Implementation of a pretensioned, fully bonded bolting system and its failure mechanism based on acoustic emission: A laboratorial and field study", *Geotech. Test. J.*, **40**(6), 978-999.

Gao, F.Q., Stead, D. and Kang, H.P. (2014), "Simulation of roof shear failure in coal mine roadways using an innovative UDEC Trigon approach", *Comput. Geotech.*, **61**(3), 33-41.

Hua, X.Z., Ma, J.F. and Xu, T.J. (2005), "Study on controlling mechanism of surrounding rocks of gob-side entry with combination of roadside reinforced cable supporting and roadway bolt supporting and its application", *Chin. J. Rock Mech. Eng.*, **24**(12), 2107-2112.

Hua, Y., Nie, W., Cai, P., Liu, Y., Peng, H. and Liu, Q. (2018), "Pattern characterization concerning spatial and temporal evolution of dust pollution associated with two typical ventilation methods at fully mechanized excavation faces in rock tunnels", *Powder Technol.*, **334**, 117-131.

Huang, W.P., Li, C., Zhang, L.W., Yuan, Q., Zheng, Y.S. and Liu, Y. (2018a), "In situ identification of water-permeable fractured zone in overlying composite strata", *J. Rock Mech. Min. Sci.*, **105**, 85-97.

Huang, W.P., Yuan, Q., Tan, Y.L., Wang, J., Liu, G.L., Qu, G.L. and Li, C. (2018b), "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. Technol.*, **73**, 26-36.

Huang, Y.C. and Sun, H.H. (1997), "Rules of ground pressure and strata control in gateways maintained in goaf", *J. China Coal Soc.*, **22**(2), 128-131.

Jiang, B.Y., Wang, L.G., Lu, Y.L., Sun, X.K. and Jin, G. (2016), "Ground pressure and overlying strata structure for a repeated mining face of residual coal after room and pillar mining", *J. Min. Sci. Technol.*, **26**(4), 645-652.

Jiang, L.S., Wang, P., Zhang, P.P., Zheng, P.Q. and Xu, B. (2017), "Numerical analysis of the effects induced by normal faults and dip angles on rock bursts", *C. R. Mecanique*, **345**(10), 690-705.

Jiang, Y.D., Wang, H.W., Zhao, Y.X., Zhu, J. and Pang, X.F. (2011), "The influence of roadway backfill on bursting liability and strength of coal pillar by numerical investigation", *Procedia Eng.*, **26**, 1125-1143.

Kang, H.P., Lin, J. and Fan, M.J. (2015), "Investigation on support pattern of a coal mine roadway within soft rocks-a case study", *J. Coal Geol.*, **140**(15), 31-40.

Komurlu, E., Kesimal A. and Demir, S. (2016), "Experimental and numerical analyses on determination of indirect (splitting) tensile strength of cemented paste backfill materials under different loading apparatus", *Geomech. Eng.*, **10**(6), 775-791.

Lee, Y.J. (2016), "Determination of tunnel support pressure under the pile tip using upper and lower bounds with a superimposed approach", *Geomech. Eng.*, **11**(4), 587-605.

Li, H.M. (2000), "Control design of roof rocks for gob-side entry", *Chin. J. Rock Mech. Eng.*, **19**(5), 651-654.

Liu, K., Chan, E., Lee, V., Kapitanova, K. and Son, S.H. (2013), "Design and evaluation of token-based reservation for a roadway system", *Transport. Res. C Emer. Technol.*, **26**, 184-202.

Liu, Q., Nie, W., Hua, Y., Peng, H.T. and Liu, Z.Q. (2018a), "The effects of the installation position of a multi-radial swirling air-curtain generator on dust diffusion and pollution rules in a fully-mechanized excavation face: A case study", *Powder Technol.*, **329**, 371-385.

Liu, X.S., Ning, J.G., Tan, Y.L. and Gu, Q.H. (2016), "Damage constitutive model based on energy dissipation for intact rock subjected to cyclic loading", *J. Rock Mech. Min. Sci.*, **85**, 27-32.

Liu, Y.H., Nie, W., Jin, H., Ma, H., Hua, Y., Cai, P. and Wei, W.L. (2018b), "Solidifying dust suppressant based on modified chitosan and experimental study on its dust suppression performance", *Adsorpt. Sci. Technol.*, **36**(1-2), 640-654.

Ma, Z.G., Gong, P., Fan, J.Q., Geng, M.M. and Zhang, G.W. (2011), "Coupling mechanism of roof and supporting wall in GER in fully-mechanized mining with gangue backfilling", *Min. Sci. Technol. China*, **21**(6), 829-833.

Monjezi, M., Hesami, S.M. and Manoj, K. (2011), "Superiority of neural networks for pillar stress prediction in bord and pillar method", *Arab. J. Geosci.*, **4**(5): 845-853.

Nie, W., Wei, W.L., Cai, P., Liu, Z., Liu, Q., Ma, H. and Liu, H. (2018), "Simulation experiments on the controllability of dust diffusion by means of multi-radial vortex airflow", *Adv. Powder Technol.*, **29**(3), 835-847.

Ning, J.G., Liu, X.S., Tan, J., Gu, Q.H., Tan, Y.L. and Wang, J. (2018), "Control mechanisms and design for a 'coal-backfill-gangue' support system for coal mine gob-side entry retaining", *J. Oil Gas Coal Technol.*, **18**(3-4), 444-466.

Ning, J.G., Wang, J., Tan, Y.L., Zhang, L.S. and Bu, T.T. (2017a), "In situ investigations into mining-induced overburden failures in close multiple-seam longwall mining: A case study", *Geomech. Eng.*, **12**(4): 657-673.

Ning, J.G., Wang, J., Jiang, J.Q., Hu, S.C., Jiang, L.S. and Liu, X.S. (2017b), "Estimation of crack initiation and propagation thresholds of confined brittle coal specimens based on energy dissipation theory", *Rock Mech. Rock Eng.*, **51**(1), 119-134.

Schumacher, F.P. and Kim, E. (2014) "Evaluation of directional drilling implication of double layered pipe umbrella system for the coalmine roof support with composite material and beam element methods using FLAC3D", *J. Min. Sci.*, **50**(2), 335-338.

Singh, G.S.P. (2015), "Conventional approaches for assessment of caving behaviour and support requirement with regard to strata control experiences in longwall workings", *J. Rock Mech. Geotech. Eng.*, **7**(3), 291-297.

Sun, H.H., Wu, J. and Qiu, Y.X. (1992), "Rules of ground pressure

and strata control in gateways maintained in goaf", *J. China Coal Soc.*, **17**(1), 15-21.
Tan, Y.L., Yu, F.H., Ning, J.G. and Zhao, T.B. (2015a), "Design and construction of entry retaining wall along a gob side under hard roof stratum", *J. Rock Mech. Min. Sci.*, **77**, 115-121.
Tan, Y.L., Liu, X.S., Ning, J.G. and Tian, C.L. (2015b), "Front abutment pressure concentration forecast by monitoring cable-forces in the roof", *J. Rock Mech. Min. Sci.*, **77**, 202-207.
Tan, Y.L., Liu, X.S., Ning, J.G. and Lu, Y.W. (2017), "In Situ Investigations on failure evolution of overlying strata induced by mining multiple coal seams", *Geotech. Test. J.*, **40**(2), 244-257.
Tan, Y.L., Liu, X.S., Shen, B.T., Ning, J.G. and Gu, Q.H. (2018), "New approaches to testing and evaluating the impact capability of coal seam with hard roof and/or floor in coal mines", *Geomech. Eng.*, **14**(4), 367-376.
Wang, F.T., Zhang, C., Wei, S.F., Zhang, X.G. and Guo, S.H. (2016), "Whole section anchor-grouting reinforcement technology and its application in underground roadways with loose and fractured surrounding rock", *Tunn. Undergr. Sp. Technol.*, **51**, 133-143.
Wang, H., Nie, W., Cheng, W.M., Liu, Q. and Jin, H. (2018), "Effects of air volume ratio parameters on air curtain dust suppression in a rock tunnel's fully-mechanized working face", *Adv. Powder Technol.*, **29**(2), 230-244.
Wang, H.S., Zhang, D.S. and Fan, G.W. (2011a), "Structural effect of a soft-hard backfill wall in a gob-side roadway", *Min. Sci. Technol. China*, **21**(3), 313-318.
Wang, H.W., Poulsen, B.A., Shen, B.T., Xue, S. and Jiang, Y.D. (2011b), "The influence of roadway backfill on the coal pillar strength by numerical investigation", *J. Rock Mech. Min. Sci.*, **48**(3), 443-450.
Wang, M., Bai, J.B., Li, W.F., Wang, X.Y. and Cao, S.G. (2015), "Failure mechanism and control of deep gob-side entry", *Arab. J. Geosci.*, **8**(11), 9117-9131.
Wu, X., Jiang, Y., Guan, Z. and Wang, G. (2018), "Estimating the support effect of the energy-absorbing rock bolt based on the mechanical work transfer ability", *J. Rock Mech. Min. Sci.*, **103**, 168-178.
Xue, D.P., Wang, J.P., Tu, H.S., Wang, F.T. and Zhao, J. (2013), "Deformation failure mechanism and application of the backfill along the goaf-side retained roadway", *J. Min. Sci. Technol.*, **23**(3), 329-335.
Yang, D.W., Ma, Z.G., Qi, F.Z., Gong, P., Liu, D.P., Zhao, G.Z. and Zhang, R.R. (2017), "Optimization study on roof break direction of gob-side entry retaining by roof break and filling in thick-layer soft rock layer", *Geomech. Eng.*, **13**(2), 195-215.
Yang, H.Y., Cao, S.G., Wang, S.Q., Fan, Y.C., Wang, S. and Chen, X.Z. (2016), "Adaptation assessment of gob-side entry retaining based on geological factors", *Eng. Geol.*, **209**, 143-151.
Ying, X., Jin, C. and Bai, J.B. (2016), "Control of floor heaves with steel pile in gob-side entry retaining", *J. Min. Sci. Technol.*, **26**(3), 527-534.
Zhang, D.S., Ma, L.Q., Miao, X.X. and Dong, G.W. (2006), "Factor analysis on deformation of gob-side entry retaining with entry-in packing in top-coal caving mining face", *J. China Univ. Min. Technol.*, **35**(1), 1-6 .
Zhang, G.C., He, F.L., Jia, H.G. and Lai, Y.H. (2017), "Analysis of gateroad stability in relation to yield pillar size: A case study", *Rock Mech. Rock Eng.*, **50**(5), 1263-1278.
Zhang, N., Yuan L., Han C.L., Xue, J.H. and Kan, J.G. (2012), "Stability and deformation of surrounding rock in pillarless gob-side entry retaining", *Safety Sci.*, **50**(4), 593-599.
Zhang, Q., Zhang, J.X., Guo, S., Gao, R. and Li, W.K. (2015), "Design and application of solid, dense backfill advanced mining technology with two pre-driving entries" *J. Min. Sci. Technol.*, **25**(1), 127-132.
Zhao, T.B., Fang, K., Wang, L., Zou, J. and Wei, M. (2017a), "Estimation of elastic modulus of rock using modified point-load test", *Geotech. Test. J.*, **40**(2), 329-334.
Zhao, T.B., Guo, W.Y., Tan, Y.L., Lu, C.P. and Wang, C.W. (2017b), "Case histories of rock bursts under complicated geological conditions", *Bull. Eng. Geol. Environ.*, 1-17.
Zhao, T.B., Guo, W.Y., Tan, Y.L., Yin, Y.C., Cai, L.S. and Pan, J.F. (2018), "Case studies of rock bursts under complicated geological conditions during multi-seam mining at a depth of 800 m", *Rock Mech. Rock Eng.*, **51**(5), 1539-1564.
Zhang, Z.Z., Bai, J.B., Chen, Y. and Yan, S. (2015), "An innovative approach for gob-side entry retaining in highly gassy fully-mechanized longwall top-coal caving", *J. Rock Mech. Min. Sci.*, **80**, 1-11.
Zhou, Z.L., Chen, L., Cai, X., Shen, B.T., Zhou, J. and Du, K. (2018), "Experimental investigation of the progressive failure of multiple pillar-roof system", *Rock Mech. Rock Eng.*, **51**(5), 1629-1636.

CC

Symbols

a	roadway width
b	gob-side backfill width
c	hanging length of rock beam B
h	mining height
h_1	initial thickness of the coal seam
h_2	initial thickness of gob-side backfill
h_3	initial height of the roadway
h_4	thickness of the flexible materials
h_m	separation between the lateral main roof and gangues in goaf before rotation of rock beam A
h_C	height of coal wall used in the testing system
L_0	horizontal distance from the fracture line to the edge of coal wall
L_1	length of rock beam A
L_2	bearing length of gangues in goaf
θ	rotation angle of rock beam A
m_z	thickness of the immediate roof
γ_Z	gravimetric density of the immediate roof
G_Z	weight of rock beam B
G_E	weight of rock beam A
K_m	initial bulking coefficient of gangues in goaf
K_G	largest compression ratio of gangues C at the rotation angle of θ
K_{F2}	largest compression ratio of the flexible material
Δh	initial subsidence at the end of rock beam B
Δh_M	deformation of coal wall at the rotation angle of θ
Δh_G	largest deformation of gangues C at the rotation angle of θ
Δh_F	mean deformation of gob-side backfill at the rotation angle of θ
Δh_C	deformation of coal wall in the testing system
ε_{M1}	virgin strain of the coal seam
ε_{M2}	largest strain of the coal wall at the rotation angle of θ
ε_F	mean strain of gob-side backfill at the rotation angle of θ
q	uniform load produced by the overlying soft strata
q_{M1}	smallest supporting force of coal wall

q_{M2}	largest supporting force of coal wall
q_F	supporting force of gob-side backfill
q_G	largest supporting force of gangues in goaf
d_S	internal diameter of the individual prop
p_S	value measured by the pressure gauge of the testing system
S_M	superficial area of coal wall used in the test
n	number of individual props used in the test
M_D	bending moment at D side of rock beam B
W_D	bending section modulus
$[\sigma]$	allowable bending stress of rock beam B