Cooperative load-bearing characteristics of a pillar group and a gob pile in partially caved areas at shallow depth

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Abstract
Stress concentration in partially caved goaf is the main cause of dynamic pressure accident in the lower seam mining. Aimed at the characteristics of caving in shallow partially caved goaf (PCG) and the specificity of interior load-bearing structures, a classification criterion of goaf caving was proposed. The characteristics of cooperative load-bearing in pillar group and gob pile were revealed by numerical calculation, physical simulation, and theoretical analysis. Taking intermittent mining as an example, combined with the deformation behaviors of the main roof and the loading characteristics of waste rock mass, the characteristics of the load-bearing of gob piles were described in the form of a piecewise function. A FLAC3D model of intermittent mining is modeled to evaluate the stability of pillars, the long-term stability and distribution laws of overlying loads were revealed through a refined model. The results show that the width of the caved zone bearing the load in the intermittent goaf is about 20 m, and the maximum load-bearing capacity is 1.055 MPa. The maximum depth of the plastic region in one side of the pillar is 1.48 m, and the load on elastic zone is about 11.33 MPa. This study provides a method for the study of the caving characteristics and load uncertainty in PCG, and the results provide important theoretical values for the safe mining of lower coal seams.

KEYWORDS
gob pile, load-bearing characteristics, partially caved goaf, pillar group, shallow coal seams mining

1 | INTRODUCTION

The occurrence of mineable coal seams in western China is characterized by shallow burial, multiple layers, and small spacing between layers, the Yushenfu mining area is the most representative. The upper coal seams have been almost mined out, and the mining methods mainly include room mining, longwall fully mechanized mining, and interval mining. Interval mining includes strip mining, pillar mining, and the intermittent mining, intermittent mining is unique to the Yushenfu mining area, the layout of intermittent working face is the same as that of longwall face, which mining 35-50 m and then leaving a coal pillar with a width of 10-15 m. Dynamic pressure is generally exist in lower working face during passing through the upper residual pillars; however, they are more intensive and intense under the partially caved gob (PCG). For example, #30107 working face under the intermittent gob in Nanliang Coal Mine, in addition to four times of support failures(SF) through pillars, seven times of SF under the gob had occurred when the working face was
advanced 190 m. The literatures show that the stress-concentrated zone in the upper goaf is the main cause of the SF.\textsuperscript{1-3} The existing researches on bearing characteristic in mined area are mostly concentrated on the overlying load distribution of pillars, there are few reports on the cooperative bearing of pillar and gob pile. Therefore, it is very essential for it to study the distribution law of concentrated load in the PCG, and there are important theory and practical value.

Recent research achievements have been made on shallow coal seams mining. Huang has proposed the definition of shallow-buried coal seam based on key stratum, base-load ratio, and buried depth, and also found that there are only caved zone and fracture zone in the overlying strata of shallow goaf.\textsuperscript{4} There are caved zone, fracture zone, and continuous deformation zone of movement in the overburden rock mass after coal mining,\textsuperscript{5-11} which has been widely used in China.\textsuperscript{12-16} Combined with field measurement and physical simulation, Huang and Wang\textsuperscript{12-16} revealed that the shallow coal seams are covered with a single key stratum structure, fracture zone develops directly to the surface while key blocks losing stability, which is also the key factor to induce hydraulic support failures (SF) and other hazards.\textsuperscript{17-22} SF has become more prominent when mining under the goaf. Ju\textsuperscript{2} has revealed the fundamental mechanism of the support failures (MSF) when longwall faces cut across below the upper pillars, Wang\textsuperscript{3,23} has provide the MSF when longwall mining under a room mining goaf, Zhu\textsuperscript{24,25} has present the MSF under double-layer room goaf by a case study. Deep-hole presplit blasting technology was presented to avoid the accident by Wang and others.\textsuperscript{24-27} These studies focused on the room mining and fully mechanized mining goafs; however, the caved zone can be further divided into the noncaved, fully caved zone, and the nonfully caved,\textsuperscript{28} especially in the case of nonfully caved goar, bearing structures are special and the bearing characteristics are very complex. Although the bearing characteristics of pillar and gob pile are studied by different methods respectively,\textsuperscript{29-31} but it is the basis of research to find out load-bearing characteristics of pillar group cooperatively with waster rock mass in shallow nonfully caved goaf.

Taking the intermittent mining as an example,\textsuperscript{29-31} the research in the characteristics of cooperative load-bearing of pillar and broken rock in caved zone will be carried out in this study. First, the caving patterns of roof and interior load-bearing structures in residual goaf mined with various methods will be analyzed, criteria of judging various caving patterns of goaf will be proposed, and the term PCG will be defined. For intermittent mining, the characteristics of roof caving will be analyzed, and the stability of pillars will be evaluated using the methods of a field survey, physical simulation, numerical calculation, and theoretical analysis. Combined with the characteristics of bending deformation in the main roof as well as the characteristics of load-bearing in broken rock, the width and strength of a caved zone in goaf will be determined. A research model of pillars will be established to study the characteristic of load-bearing in the long term. The distribution features of plastic regions inside pillars and the distribution laws of overlying loads will be researched, and thus characteristics of cooperative load-bearing in pillar group gob pile in shallow partially caved areas will be revealed.

2 DEFINITION OF PCG (PARTIALLY CAVED GOAF)

There are various caving patterns of shallow goafs, dividing the goaf into different types help research concerning the features in the breaking of overlying strata in various types of goafs, the laws of load-bearing structures distributed in the goaf and concentrated stresses, the laws of the propagation of concentrated stresses in the roof of lower coal group, as well as the laws of roof breakage during the mining process of lower coal group, etc.

According to the caving status of the overlying strata, criteria for judging various types of goaf in shallow coal seams are proposed as follows:

\begin{equation}
\begin{array}{l}
\{ h_c \times BF \leq h, \text{(Non − caved goaf)} \\
\{ h_c \times BF + w_m \geq h, \text{w_m} \in \text{float}, \text{Bending zone is in overburden, (Partially caved goaf)} \\
\{ \text{w_m} = \text{null}, \text{No bending zone, (Fully caved goaf)}
\end{array}
\end{equation}

where $h_c$ is the height of the caved zone, BF is the bulking factor of the caved waster, $w_m$ is the maximum bending subsidence of strata, and $h$ is the mining height.

Goafs formed by different mining methods as shown in Figure 1 are divided according to the criteria in Equation (1) and the above analysis. Figure 1(A), Figure 1(B), and Figure 1(C) show uncaved goaf formed by a room mining method, PCG mined by intermittent mining, and fully caved goaf formed by a fully mechanized longwall mining method, respectively. However, fully mechanized longwall mining goaf should be divided into two regions for discussion, region A (adjacent to the pillar) and B (further away from the pillar) shown in Figure 1(C), region B was fully caved, and region A is PCG.

In various types of goaf, the differences exist not only in the caved ranges of roofs but also in the load-bearing structures and laws of concentrated loads distributed in goafs. In uncaved goaf, the caved height of the roof is much smaller than the mining height, and pillars are the only load-bearing structure. In PCG, where part of the roof in a goaf is caved and broken rock is partially connected with the bending subsidence zone, the pillar and gob pile are the load-bearing structure. In fully caved goaf, the overlying
The caved zone and fracture zone are developed to the ground surface, with no bending deflection zone formed, and the load-bearing structure is similar to that in PCG. However, the breaking patterns of the roof are cutting-off breaks and bench subsidence in shallow coal seams. Therefore, relative to PCG, in fully caved goaf, the caving angle is larger, the load-bearing capacity of the broken roof is much larger, while the overlying load of the pillar is smaller.

The residual status of pillars and the environment around the load-bearing structure in PCG are special, as shown in Figure 1. This is mainly reflected in the following aspects: (a) The shapes of the pillars are different. During room mining, the pillars are set with small dimensions, of which both length and width are smaller than 10 m and distributed in a chessboard pattern. During intermittent mining, the pillars are set with larger dimensions, of which the width ranged from 5 to 10 m and the length ranged from 100 to 200 m are parallelly distributed.32 (b) The environment around the load-bearing structure is different. During room mining, there is uncaved goaf around the pillars, and adjacent pillars co-carry the weight of the overlying strata in the goaf. During intermittent mining, the overlying strata in the goaf are partially caved; pillars do not carry the weight of the overlying strata just above the pillars, nor the entire overlying strata. Due to roof caving characteristics, there is a significant uncertainty in the load-bearing of pillars.

The element of load-bearing structure in PCG is the pillar–gob pile, the dimensions of which are detailed in Figure 2.
Roof caving status in goaf should be determined first before beginning to research the laws of distribution in overlying loads as well as the characteristic of cooperative load-bearing of caved waster and pillars in the goaf.

3 | ROOF CAVING IN PCG (PARTIALLY CAVED GOAF)

The determination of caving status of goaf roof is the sufficient condition for carrying out research in the characteristics of load-bearing in caved waster. Features of stability in goaf roofs during intermittent mining were inverse analyzed in this section combining physical simulation and numerical calculation.

3.1 | A case study

The #2-2 coal seam in Nanliang coal mine is mined with intermittent mining methods, of which the working face was arranged along an advancing direction, and is advanced at intervals along the inclination. In other words, the open-off cut in the working face was 200 m long, then a 10 m pillar is situated every 50 m, and then the working face is moved to a new open-off cut and continued to advance.\(^{33}\) By the intermittent mining method, the working section recovery is much larger than that in room mining, and disasters due to dynamic pressure induced by too large a step distance in first weighting can be prevented. The histogram of boreholes in Figure 3 reveals the occurrence features of the overlying strata. Laboratory testing results of the strength of overlying strata are listed in Figure 3(B).

3.2 | Physical simulation

A physical model is built to investigate the stability status of goaf and pillars during intermittent mining. As shown in Figure 4, the dimension of the physical model is 2.5 × 2.0 × 0.3 m with a geometric similarity ratio of 1:100. Considering the effects of landform on caving characteristics, the upper surface of the model represented the ground surface, including gentle and gully geomorphology with slope angles of 30° and 45°, respectively. The bottom surface of the model represents the immediate floor in the #3-1 coal seam. A label paper is fixed at grid point as an identification point for monitoring the strata movement.

Monitoring the variation in displacement of the identification point revealed the characteristics of the roof deformation. As shown in Figure 6, the change in displacement in the immediate roof was concave with two peak points and a vertical displacement of about 2.0 m, which indicates that the immediate roof is bending and subsiding at both sides and fully caving in the middle. The change in displacement in the main roof also was concave yet with only one peak point, indicating that the main roof bended and subsided with a maximum subsidence of about 1.15 m in the middle.

3.3 | Numerical simulation

The discrete element method (DEM) is a numerical simulation method specifically designed for solving the problem of discontinuous mediums. The three-dimensional discrete element geological model is established by the discrete element method, which analyzes the features of the stability of the overlying strata in the goaf. A numerical model is built as shown in Figure 7 according to a surface-underground contrast plan, a general stratigraphic column and the mechanical parameters of the rocks. The Delaunay triangular element is used to reconfigure the actual landform. A constitutive model of blocks and joints is described using the Mohr–Coulomb
model and the joint area contact elastic/plastic Coulomb slip failure model, respectively. Properties of block and joint were calibrated by 3DEC. There is no displacement constraint on the upper surface of the model (the ground surface). For the other sides, displacements in the normal direction are fixed to 0, and the coefficient of horizontal pressure is 1.25.

The features of stability in the goaf roof are revealed through numerical calculations. As shown in Figure 8, when all goafs are formed after mining, in order to determine the caving patterns of the goaf roof, the I-I section along the advancing direction and the II-II section along the inclination are shown in Figure 8(B) and Figure 8(C), respectively and are taken out to investigate the stability of the roof strata (blocks). Figure 8(B) shows that, when the immediate roof is fully caved, the main roof is bent and subsided, and the main roof at the pillars at both sides of the working face is unsupported and developed cracks. The heights of the caved zone and fracture zone are 1.5 m and about 7.5 m, respectively. Figure 8(C) shows that, during intermittent mining, the immediate roof within the range of the stopping span (50 m) has caved; the main roof is bent as well as subsided with larger subsidence in the middle part and makes contact with the caved waster of the immediate roof.

According to the numerical calculation and physical simulation results, it can be determined that the caving mode of the roof in PCG is as follows: the false roof and immediate roof are caved, and the main roof is bent and subsided with highly developed cracks in the middle.
LOAD-BEARING CHARACTERISTICS OF BROKEN ROCK MASS

As one of the load-bearing structures in PCG, there were various factors affecting the gob pile's load-bearing characteristics including the bulking factor, the strength of rocks and joints, and the features of the roof deformation. Moreover, the environment where the caved rock is located is hidden and dangerous; therefore, in this section, a model of broken rock is established by numerical simulation based on the 3D Voronoi element. The compaction characteristics of the broken rock mass are studied through experiment, and the load-bearing width and strength of the gob pile are finally determined according to the deformation features in the roof strata.

4.1 | Numerical simulation

Figure 9 shows the flowchart of the investigation into the compaction characteristics of broken rock. This included modeling, properties assignment, and uniaxial compression testing.35

4.1.1 | Modeling

The relationship between the bulking factor (BF) and the void rate (n) of the broken rock is expressed as follows:

\[
BF = \frac{1}{1-n}
\]  

First, a cubic model of the rock with an edge length of 1 is established by the 3D Voronoi block element as shown in Figure 10 with a void rate of 0. Then, a preset void rate is achieved by randomly deleting blocks in the model and is shown in Figure 10(B). Finally, the model of broken rock mass is established as shown in Figure 10(C).

4.1.2 | Properties assignment

The properties of the rock and joints are assigned in following steps:

FIGURE 5 Sketch of intermittent mining model in #2-2 coal seam

FIGURE 6 Vertical displacement of the roof strata

FIGURE 7 Numerical model
1. Joints in the broken rock are divided into two groups according to their locations: external contact and interior contact; 
2. Blocks are set as elastic elements; joints are set as a Coulomb sliding model. Tensile strength and cohesive force of the external joints are set to 0; 
3. Combined with the calibrated mechanical properties of the rock and joints, parameter arrays in accord with Weibull distribution are constructed; 
4. The properties of blocks and joints are assigned by the commands “zone,” “property” and “c_mat(CONTACT_IND).”

4.1.3 | Uniaxial compression testing

Loading plates were added to the upper and lower surfaces of the broken rock model, on which then a uniaxial compressive test is performed using a loading method of velocity. The Fish is programed to monitor its deformation characteristics. Four sets (ie, eight) of monitoring points with a vertical distance of 0.1 m to the model boundaries are arranged on the upper and lower surface of the model to monitor strain. Stress is the average value of stresses in the cubic local element with edge length of 0.5 m in the center of the model.

Figure 11 shows the curves of characteristics in load-bearing and deformation in the broken rock mass, which is obtained by stress–strain monitoring, and the applicability of the result is examined by comparing calculation results with published experiment data. The polynomial fitting formula is as follows:

$$σ_{wrm} = -3e^3 \varepsilon_{wrm}^3 + 1e^2 \varepsilon_{wrm}^2 + 474153e_{wrm} - 112614 \quad (3)$$

where $σ_{wrm}$ and $\varepsilon_{wrm}$ are the stress component and strain in the vertical direction of the broken rock mass, respectively.

4.2 | Load-bearing characteristics of broken rock mass in PCG

4.2.1 | Deformation behavior of the main roof

In the Shenfu mine area, gully landform is dominant, and the overlying load above the main roof is linear. The clamped–clamped beam model as shown in Figure 12 is established in order to analyze the bending deformation characteristics of the main roof, on the upper surface of which model the maximum and minimum loads as $q_1$ and $q_0$, respectively. Take a gully with a slope angle of 30°, for example, in which the properties of the main roof are as follows: a volume–weight $\gamma$ of 0.022 MN/m$^3$, a Poisson's ratio $\mu$ of 0.31, an elasticity modulus $E$ of 4.9 GPa, a buried depth $H$ of 94 m, a span $L$ of 50 m, and a thickness $h_b$ of 8 m. Analytical solutions for the displacement component...
of the main roof in the vertical direction are obtained, and a contour plot is shown in Figure 13. This shows that the vertical displacement in the main roof is symmetrically distributed with displacements of zero at both ends, while displacements in the middle were large with a maximum value of about 1.43 m.

4.2.2 Width and strength of the concentrated load on the gob pile

In PCG, the contact area between the gob pile and the strata in a bending subsided roof is the load-bearing area in the broken rock, the flat surface of which is considered to be the load-bearing width. According to the description of the PCG caving status in Section 3, it can be seen that the height of the caved zone can be expressed as follows:

\[ h_c = h_i + h_f + c \]  

where \( h_i \) is average height of the immediate roof, \( m \); \( h_f \) is the average height of the false roof, \( m \); and \( c \) is the average height of the crack transfixion area in the strata of the main roof, \( m \).

The bulking characteristics of the rock in the goaf of a shallow coal seam can be expressed as:

\[ BF = -0.1 \ln \sigma_{wrm} + 1.28 \]  

where \( \sigma_{wrm} \) is the axial load of broken rock, MPa.

According to Figure 14 and Equation (5), the initial bulking factor and residual bulking factor of the gob pile of a shallow coal seam are 1.75 and 1.28, respectively. Figure 11 shows that, in the goaf, the maximum load that broken rock can bear is the weight of the overlying strata, and the maximum strain is 0.22.

The relationship between the variation in bulking factor and loading strain of broken rock is described in the following equation:

\[ (BF - BF_t) \times h_c = \varepsilon_{wrm} \times h_c \]  

\( BF_t \) is the initial bulking factor.
where BF is the real time bulking factor of the broken rock during the loading process; \( h_c \) is the height of the caved zone in goaf during intermittent mining, \( m \); and \( \varepsilon \) is the strain of the broken rock mass.

When the height of the caved zone in goaf during intermittent mining is calculated using Equation (4), it is assumed that \( c \) is zero given that the height of the caved zone is 2.7 m. The height of the broken rock is then determined to be 2.7 \( \times \) BF. According to Equation (6), the variation in the bulking factor is equal to the axial strain of the broken rock, and so the bulking factor of the broken rock can be described as:

\[
BF = \varepsilon_{\text{wrm}} + BF_t
\]  
(7)

When the maximum axial strain is 0.22, the bulking factor of the broken rock mass in the roof is 1.47, the average heights of the false roof and the immediate roof are 2.7 m, and the height of the broken rock in the caved zone is 3.969 m. It can be seen that when \( c \) is zero, bending deformation has not occurred in the main roof yet, and the main roof is an absciss layer with a gap height of 0.931 m.

Combined with Equation (3), the equation that expresses the deformation characteristic of the broken rock mass in PCG is given as follows:

\[
\varepsilon_{\text{wrm}} = \frac{v - h_m - h_c + (h_c \times BF)}{h_c \times BF} = \frac{v - h_m - h_c + [(h_i + h_f + c) \times BF]}{(h_i + h_f + c) \times BF}
\]  
(8)

where \( v \) is the bending subsidence of the main roof.

Taking the vertical displacement in the main roof and the distance from the broken rock mass to the roof strata as critical points, combined with Equation (3), the characteristics of load-bearing in the broken rock mass in PCG are described in the form of a piecewise function as follows:

\[
\sigma_{\text{wrm}} = \begin{cases} 
0; & v \leq h_i + h_m - h_c \times BF \\
-3e^3\varepsilon_{\text{wrm}}^3 + 1e^3\varepsilon_{\text{wrm}}^2 + 474 153\varepsilon_{\text{wrm}} - 112 614; & v > h_i + h_m - h_c \times BF
\end{cases}
\]  
(9)

Figure 15 shows the distribution of stress–strain in the vertical direction of the broken rock mass in PCG. Caved waster at both ends in the goaf did not make contact with the roof. Only the caved waster in the middle carried loads with a load-bearing width of 20 m and a maximum carried load of 1.055 MPa.

5 | STABILITY AND LOAD-BEARING CHARACTERISTICS OF PILLARS IN PCG

5.1 | Evaluation of pillar group stability

The numerical simulation method is used to study the behaviors of the plastic zone distributed in the pillars and evaluate pillar stability. The geological model of the working face during intermittent mining is reconfigured, as shown in Figure 16, based on ground topographic contours, histograms of strata, and lithology parameters. All zones are tetrahedrons. The Mohr–Coulomb model is used as the constitutive model.38 Properties of zone were calibrated by RocData program. There were no constraints of stress and displacement on the upper surface of the model. Other surfaces had displacement constraints in the normal direction with a horizontal stress coefficient of 1.25.

Numerical results revealed the distribution characteristics of plastic zones in pillars. Figure 17 shows a section profile of goaf in the model. The numerical results of the intermittent pillar in the local No. 20113 working face show that the middle of the pillar is an elastic region, while the two sides are plastic zones with a plastic type dominated by shear failure.
The surface grounds of the No. 20111 and No. 20113 intermittent goafs included gully and gentle landforms. The distribution characteristics of plastic regions in pillars indicate that pillars under both landforms are stable.

5.2 Load-bearing characteristics of the intervening pillar

A numerical model of pillars is established to investigate its long-term load-bearing characteristics. Figure 18 shows the model dimensions and element meshing. There is no displacement constraint on the two sides of the pillar and the upper surface of the model. Other surfaces had zero displacement in the normal direction. All zones in the model are tetrahedrons. The edge length gradually increased from the two ends to the middle in the pillar with minimum and maximum edge lengths of 0.15 and 1.5 m, respectively. As the residual pillar would carry loads for a long time, the rheology characteristics need to be considered. The Burgers–Mohr rheology model is used to simulate pillar elements with parameters as listed in Table 1. The Mohr–Coulomb model is used to simulate elements in other strata with properties as listed in Figure 3(B).

The numerical calculation revealed the plastic development characteristics of the pillar elements as shown in Figure 19. There are plastic zones dominated by shear failure with a maximum depth of 1.48 m distributed at the two sides of the pillar. Within the plastic region, it is a stress-release region, while within the elastic region, it is a stress-concentrated region.

The vertical stress of the elements in the middle of the pillar is extracted to plot the curves of the distribution laws of the overlying concentrated loads above the pillar, as shown in Figure 20. Two sides of the curve are stress-release regions (plastic regions), and the middle part of the curve is the stress-concentrated region (elastic
region), which are fitted by a piecewise linear function and a Gaussian approximation function, respectively. The fitting results revealed the distribution laws of concentrated stresses above the pillar.

The piecewise linear fitting expression is given as follows:

\[
\begin{align*}
\sigma_p = & \left\{ \begin{array}{l}
5e^6x + 3e^7 \\
2612.6x^6 - 2047.3x^5 - 36531x^4 + 21750x^3 + 116086x^2 - 47344x + 1e7 \\
-5e^6x + 3e^7
\end{array} \right. \\
\end{align*}
\]

Here, the load-bearing characteristics of the pillar–gob pile in partially caved area are revealed. The result can be used to study the propagation laws of concentrated loads in the floor, also providing theoretical support for the safe mining of the lower coal seams.

6 | DISCUSSION

The main difference between noncaved goaf, fully caved goaf, and partially caved goaf is the bearing structure. As
shown in Figure 1, the coal pillars in the noncaved goaf bear the full weight of the overburden, the weight of the overburden in the fully caved goaf is borne by the caved waster, but the bearing structure in the partially caved goaf is pillar and caved waster. The load-bearing structure is different in different types of goaf, and the load distribution characteristics in goaf are also different, according to the above classification results of shallow goaf, the bearing characteristics of bearing structure in goaf are discussed in three categories which shown in Figure 21, and the difference of load distribution in three types of goaf is analyzed as follow.

Fully caved goaf as shown in Figure 21(A), taking fully mechanized mining goaf as an example, most of the coal pillars in fully caved goaf are chain pillars with a width of 10-15 m. The distribution law of overlying load and the stability characteristics of coal pillars are affected by mining stress, there is a certain width of plastic zone on both sides, if the middle of the pillar is elastic zone, the overlying load curve is M-shaped, if the pillar is completely plastic, the load distribution on the pillar is arch-shaped. The overburden strata of shallow coal seam are mostly broken by cutting, and the fracture zone develops to the surface, the gob pile in the goaf can be divided into two regions to bear the overlying strata: Region A which near the pillar, due to the support of the coal pillar, the caved waster in this area cannot fill the goaf, the gob pile is partly roofed, the overlying load is related to the subsidence of the roof. The method of determining the load is similar to the method of determining the bearing characteristics of the PCG mentioned above; Region B which far from the coal pillar, the caved waster in this region is fully roofed and compacted, and the bearing load is the weight of the overlying strata. The compaction characteristics of caved waster are determined by compression test, and the settlement characteristics of overburden are determined by field measurement and numerical simulation, combining the characteristics of caved waster compaction and overburden settlement, the bearing characteristics of coal pillar and gob pile in the goaf can be determined.

Noncaved goaf as shown in Figure 21(B), taking room mining goaf as an example, the width of coal pillar and room goaf is about 6-8 m, the coal pillars in the goaf are regularly

| Lithology | Shear Bulk | Shear Kelvin | Shear Maxwell | Kelvin viscosity | Cohesion | Friction | USC |
|-----------|-----------|--------------|---------------|-----------------|----------|----------|-----|
| #2-2 Coal | 2.5e3     | 1.1e3        | 1.1e3         | 2.98            | 44°      | 1.45     |

FIGURE 18 Pillar model grid

FIGURE 19 Distribution characteristics of zone state in the pillar

TABLE 1 Parameters of Burgers-Mohr model (Unit: MPa)
The calculation method of the average load on the coal pillar is as follows.

$$
\sigma_{\text{aps}} = \frac{0.025 \left[ H \left( w_1 \sin \theta + \frac{b_1}{2} + \frac{W}{2} \right) - \frac{w_1^2 \tan \beta}{8} \right] \left[ w_2 + \frac{b_2}{\sin \theta} \right]}{w_1 w_2 \sin \theta}
$$

where, $w_1$ and $w_2$ are respectively the side lengths of coal pillar, $b_1$ and $b_2$ are spacing between coal pillars, $\beta$ is caving angle, $\theta$ is interior stagger angle between boundary lines of coal pillar, and $W$ is the width of room mining face.

Due to the dense distribution of coal pillars in the room mining goaf, the above calculation method assumes that there is no plastic zone in the coal pillars, if the influence of plastic damage on the bearing characteristics of the pillars is taken into account, the overburden load distribution law of the pillars can be determined by numerical simulation.

Partially caved goaf as shown in Figure 21(C), taking interval goaf as an example, the width of the interval coal pillar is about 10m, the width of the interval goaf is 30-50 m, and the pillars are parallel to the direction of the working face, the roof of the interval goaf are partially caved, and coal pillars and caved waster in goaf bear the weight of overlying strata together. From the analysis of the 5th section above, it can be found that a certain range of plastic zones on both sides of the pillar, and the overlying load distribution law of the pillars is M-shape. The overlying load distribution law of the gob pile can be determined by combining the bearing characteristics of caved waster and the roof subsidence.

7 | CONCLUSIONS

The cooperative load-bearing characteristics of a pillar and gob pile in partially caved area were studied by the field survey, theoretical calculation, physical experimentation, and numerical simulation, from which the following conclusions can be drawn:

1. A criterion to classification the caved goaf was proposed according to the height of caved zone, bulking factor of the caved waster, deformation of the subsided zone, and the mining height.
2. The intermittent goaf was determined as PCG by simulation, numerical calculation, and field observation: The false roof and immediate roof are caved, and the main...
roof was subsided, which verified the validity of the criterion mentioned in conclusion (1). Additionally, the pillar group–gob pile is revealed as the load-bearing structure in PCG.

3. General clamped–clamped beam models of the main roof for deformation analysis under various landforms were established based on which analytic solutions of bending deformation in the main roof were calculated and obtained. The load-bearing characteristics of the waster rock mass are studied by 3DEC. An equation of overlying load above the gob pile in PCG was derived according to the analytic solutions and numerical results. Taking the gully landform as an example, it was calculated that the gob pile in PCG had a load-bearing width of about 20 m and a maximum carried load of 1.055 MPa.

4. A large-scale numerical model of the intermittent mining was established by FLAC3D, and the pillar distribution as well as the landform features in PCG was reconfigured, according to which the stability characteristics of the pillars are inversion analyzed and determined as follows: The entire pillar group was stable, but there are shear failure zones on both sides of the pillar. An expression of the laws of the overlying loads distributed in the pillar is obtained through fitting the data of the observation points. Combined with conclusion (3), the cooperative load-bearing characteristics of the pillar group and gob pile in PCG were thus revealed.

ACKNOWLEDGEMENTS

This work is supported by Independent Research Projects of State Key Laboratory of Coal Resources and Safe Mining, CUMT (SKLCRSM19KF019), the National Natural Science Foundation of China (Nos.51904200, 51874281 and 51574174) and Scientific and Technological Innovation Programs of Higher Education Institutions in Shanxi (2019L0183).

CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this paper.

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**How to cite this article:** Zhu D, Song X, Li H, Liu Z, Wang C, Huo Y. Cooperative load‐bearing characteristics of a pillar group and a gob pile in partially caved areas at shallow depth. *Energy Sci Eng*. 2020;8:89‐103. [https://doi.org/10.1002/ese3.511](https://doi.org/10.1002/ese3.511)