Bull Eng Geol Environ (2015) 74:1267–1273
DOI 10.1007/s10064-014-0685-6

ORIGINAL PAPER

The effect of a multi-gob, pier-type roof structure on coal pillar load-bearing capacity and stress distribution

J. X. Yang · C. Y. Liu · B. Yu · F. F. Wu

Received: 5 July 2014 / Accepted: 26 September 2014 / Published online: 15 October 2014
© Springer-Verlag Berlin Heidelberg 2014

Abstract In order to evaluate the effect of established gob coal pillars on the stress in lower rock strata, in the context of of mining in

Jurassic coal mine in the Datong mine field, this study theoretically analysed a collapsed roof structure in gobs of Jurassic coal strata and the physics of concentrated loads on coal pillars. The collapse state of roofing in the gobs inclined with the working face and the effect of established coal pillars on the lower rock strata were obtained. Results indicated: a stabilised natural arch structure is formed in Jurassic coal strata by squeezing of collapsed upper roof blocks inclined with the working face, and the arch springing applies a highly concentrated load on the established coal pillars; affected by the established coal pillars, the upper roof of multi-gob coal pillars appears to be a pier-type structure, used as a supporting point for the upper roof load; we propose a method of calculating the stress in the lower rock strata imparted by the coal pillars. In the context of mining Jurassic coal strata at the Tongxin coal mine in the Datong mine field, the depth of the strata affected by the concentrated stress imparted by established gob coal pillars was calculated. The effective range of energy density concentration was also calculated.

J. X. Yang · C. Y. Liu (✉) · F. F. Wu
School of Mines, State Key Laboratory of Coal Resources and Safe Mining, Key Laboratory of Deep Coal Resource Mining, Ministry of Education, China University of Mining and Technology, Xuzhou 221116, Jiangsu, China
e-mail: cyliucumt@163.com

J. X. Yang
e-mail: jxyangcumt@163.com

B. Yu
Datong Coal Mine Group Company, Datong 037003, Shanxi, China

Keywords Multi-gob · Coal pillar · Roof structure · Stress in coal pillar · Pier structure · Linear loading

Introduction

There is a significant amount of shallow buried coal strata in the mine fields of the Inner Mongol and Shanxi Provinces. Affected by room, pillar mining and small coal pit mining during early the mining stages, and due to the requirement of protecting the adjacent working face, a large amount of coal pillars were setup in the gobs of shallow buried coal strata. With an increased mining depth, mining of lower coal strata will be affected by gob coal pillars of upper coal strata. At present, Jurassic coal mining in Datong is almost complete and carbonic-age, thick and extra thick coal are becoming the primary coal strata. During the mining of Jurassic coal, a significant number of boundaries and sectional coal pillars were setup between adjacent mining wells and mining faces. When the coal strata were excavated, the lower rock roofing collapsed naturally and filled the space of the gob. For hard overlying strata, a masonry beam structure (Qian et al. 1994) is formed when the strata collapses into blocks; stability is maintained by the extrusion action between the collapsed blocks such that the self-weight and the weight of the overlying rock can be sustained. A natural arch structure is formed in the overlying strata due to horizontal extrusion forces between blocks collapsed from the overlying strata (Miao 1990; Wang et al. 2007; Du et al. 2011; Wang and He 2006). Affected by the established coal pillars in the coal strata, the weight and load of the natural arch structure of the overlying strata are sustained by the gob coal pillars. As a result, the established coal pillars are subjected to loading by the overlying strata, thereby significantly impacting the load bearing of lower strata (Yu et al. 2014). Research on the effect of established gob coal pillars has been conducted: the theoretical maximum depth affected by stress in a coal pillar under a uniformly-distributed load obtained using an elastic semi-infinite body theory was about 70 m (Yu et al. 2014); a mathematical model suitable for coal pillar dimensions has been established to ensure the stability of surface structures in regards to established gob coal pillars (Liu and Shen 1988); with the roof and floor of the face as the loading systems, interaction between coal pillars in mining roadways and underlying rock, as well as stability, have been analyzed, and the characteristics of concentrated stress distribution in coal pillars has been obtained via numerical analysis (Wang and Hou 2003); the "catastrophe" theory has been used to establish a cusp catastrophe model for rock burst induced by coal pillar instability under load, and a formula for the critical displacement used in predicting and forecasting impact failure caused by coal pillar instability has been obtained (Gao et al. 2005); the effect of established gob coal pillars in swallow buried coal strata on the mining of close-distance coal strata has been evaluated (Yang et al. 2013), etc. Presently, most relevant studies focused on the mining of lower coal strata to evaluate if the effect of upper coal pillars on the mining process of coal strata exists or not and to analyse stability issues between coal pillars and roadways. Analysis of roof collapse in gobs with established coal pillars is rare. Therefore, mining conditions of the Jurassic coal strata in the Datong mine fields was selected as the background in this study; by means of theoretical analysis, roof structures above established gob coal pillars in Jurassic coal strata, coal pillar load-bearing characteristics and the effect of concentrated loads in coal pillars were evaluated. Results from this study provide a theoretical background for analysing the effect of roof structures and Jurassic gob coal pillars on the load-bearing capacity of lower strata and the process of mining lower carbonic coal strata.

Occurrence of coal strata

Packsand, coal seams, siltite, medium-grained sands, conglomerate rock and sandy mudstone exist between the Jurassic and carbonic coal strata in the Datong mine field of the Shanxi Province. Sandy rock strata comprises 90–95 % of the lithology while muddy rock and coal strata comprise only 5–10 %.

Using mining of the Jurassic and carboniferous coal seams of the Tongxin coal mine as a background, the distance between coal seams is about 150–200 m and both seams are almost horizontal. Faces 8,202 through 8,210 of the Jurassic coal seam were completely mined from 1979–1983; the averageseamseam thickness was about 3.5 m. The carboniferous coal seam below is about 14.7 m on average, and the faces (such as faces 8,104 and 8,105) are advanced in a direction perpendicular to the strike of the mined Jurassic coal seam above. The location of working faces in the carbonic and Jurassic coal strata in the Tongxin coal mine is shown in Fig. 1.

Theoretical analysis

Analysis of multi-gob, pier-type roof structures

When excavation of a stope in approximately level coal strata commences, the rock overlaying the gob collapses into arches. When the excavation of multiple working faces commences, the arch structure consists of collapsed overlying rock in multiple gobs. Affected by the supporting action of the established coal pillars in the working faces and the caved roof angle, the roof above the coal pillars appears pier-like. As a result, a multi-gob, pier-type roof structure is formed. The characteristics of a multi-gob, rock-overlaid roofing structure is shown in Fig. 2.

In order to analyse the geometrical and load-bearing characteristics of gob pier-type roof structures in the

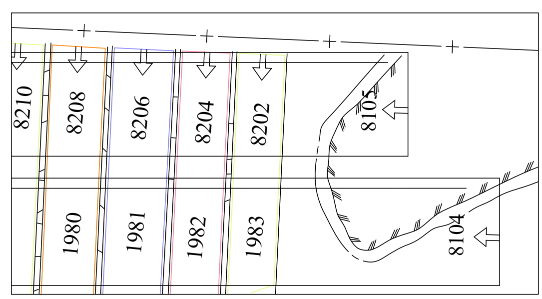


Fig. 1 Location of working faces in the carbonic and Jurassic coal strata

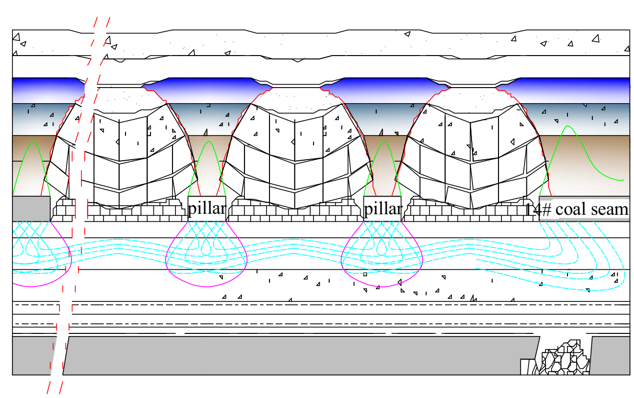


Fig. 2 Rock-overlaid, multi-gob, pier-type roof structure

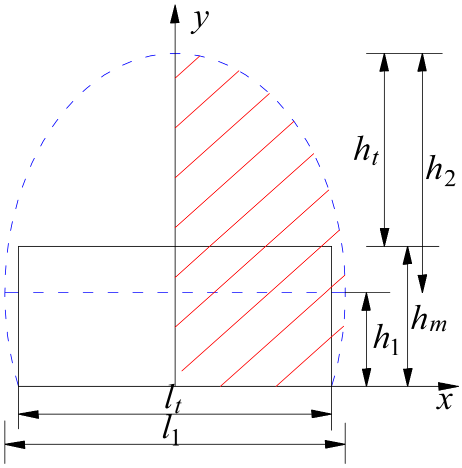


Fig. 3 Natural arch roof structure in the gobs

Jurassic coal strata of the Datong mine field, the balanced structure formed when the roof of the gobs collapses is analysed first. Dome theory is introduced to analyse the formation of the natural arch. Geometric characteristics of the natural arch structure after the roof in the gobs collapses is shown in Fig. 3.

In Fig. 3, l_1 is the width of the natural arch; h_1 is the distance from the centre of the natural arch to the floor of the coal stratum; l_t is the length of the working face in the inclined direction; h_2 is the height of natural arch; h_m is the coal strata thickness.

The geometric form of a natural arch after roof collapse is normally elliptical (Miao 1990; Wang et al. 2007; Du et al. 2011; Wang and He 2006). According to the geometric relationship in Fig. 3, the equation for a natural arch is given as:

$$\frac{4x^2}{l_1^2} + \frac{(y-h_1)^2}{h_2^2} = 1 \tag{1}$$

According to the mechanical equilibrium of a natural arch, the relationship between the width and height of a natural arch satisfies (Miao 1990) that:

$$l_1^2 = 4\eta h_2^2 \tag{2}$$

in which η is the coefficient of side compression.

The relationship between geometric dimensions of a natural arch can be calculated from Eqs. (1) and (2), combining the geometric boundary conditions in Fig. 3 as

$$\begin{cases} H = h_t + h_m = d + \sqrt{\dfrac{l_t^2 + 4d^2}{4\eta}} \\ h_1 = \dfrac{H}{2} - \dfrac{l_t^2}{8H\eta},\ h_2 = \dfrac{H}{2} + \dfrac{l_t^2}{8H\eta} \\ l_1 = H\sqrt{\eta} + \dfrac{l_t^2}{4H\sqrt{\eta}} \end{cases} \tag{3}$$

In which

$$d = \frac{l_t \tan\phi + h_m(\eta + \tan^2\phi)}{2\eta},\ \phi = \frac{\pi}{4} - \frac{\varphi}{2}$$

where: H is the distance from the top of natural arch to the floor of the coal strata; h_t is the collapsing height of the roof in the gobs; d is the intermediate variable; ϕ is the coal strata caving angle; φ is the internal rock friction angle.

In order to calculate the weight of the pier-type roof structure, the area of the shaded part in Fig. 3 is first calculated as:

$$S = \frac{l_1}{2}\int_0^{h_1+h_2} \sqrt{\left[1 - \frac{(y-h_1)^2}{h_2^2}\right]}dy \tag{4}$$

In which S is the area of the shaded part in Fig. 3.

For ease of calculation, let $\sin\vartheta = (y-h_1)/h_2$ and the area of the shaded part can be calculated as:

$$\begin{aligned} S &= \frac{l_1 h_2}{2}\int_{\vartheta_1}^{\vartheta_2} \cos^2\vartheta d\vartheta \\ &= \frac{l_1 h_2}{4}\left\{\vartheta_2 - \vartheta_1 + \frac{1}{2}[\sin(2\vartheta_2) - \sin(2\vartheta_1)]\right\} \end{aligned} \tag{5}$$

where:

$$\vartheta_1 = \arcsin\left[\frac{l_t^2 - 4\eta H^2}{l_t^2 + 4\eta H^2}\right],\ \vartheta_2 = \pi/2$$

As the pier-type roof rock strata and natural arch structure in the gobs are geometrically symmetrical, Eqs. (3), (4), and (5) can be solved simultaneously to calculate the weight of the pier-type structure as:

$$Q = \gamma[H(l_m + l_t) - 2S] \tag{6}$$

In which: Q is the weight of the pier-type roof structure; γ is the average volume weight of the roof structure; and l_m is the reserved width of the coal pillars.

According to the load-bearing characteristics of a pier-type roof structure between the rock-overlaid natural arch and its weight, the load-bearing characteristics of the roof structure is obtained and demonstrated in Fig. 4.

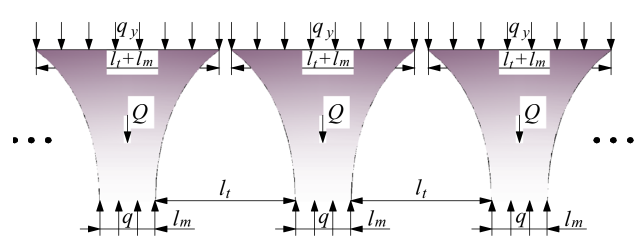


Fig. 4 Load-bearing characteristics of pier-type roof structures. $l_t = 150$ m; $q_y = 5.4$ MPa; $\varphi = 37°$; $\eta = 1.0$. The effect of coal seam thickness and coal pillar width $h_m = 3.5$ m, $q_y = 5.4$ MPa, $\varphi = 37°$, $\eta = 1.0$. The effect of working face length and coal pillar width

Due to the fact that the geometric dimensions and techniques are similar when mining adjacent working faces in the same coal strata, the rock-overlaid, multi-gob, pier-type roof structures are similar to some extent. It can be seen from Fig. 4 that if the effect of falling rock on the natural arch is neglected, the balance of the roof structure is maintained by the combined action of overlying rock strata, direct flooring of the coal strata and the self-weight of the structure. Therefore, according to the equilibrium condition of a rock-overlaid, pier-type roof structure, the supporting load of the direct flooring of the coal strata to the structure can be calculated as:

$$q = \frac{q_y(l_m + l_t) + Q}{l_m} \tag{7}$$

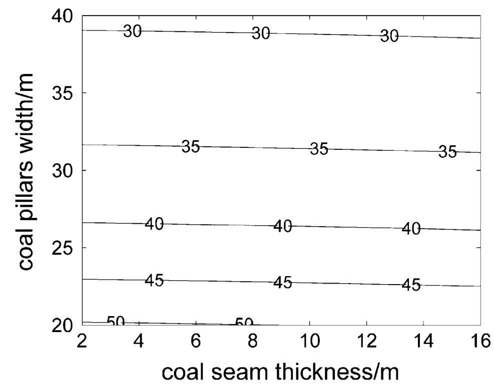
In which: q is the supporting load of the direct flooring of the coal strata to the roof structure; q_y is the acting force of the overlying rock strata on the roof structure.

Stress analysis of gob coal pillars

The direct flooring of coal strata imposes direct loading on the established gob coal pillars in a pier-type roof structure. When the occurrence of the coal strata is established, it is evident from Eqs. (5), (6), and (7) that the load carried by coal pillars is affected by the working face length and the coal pillar width. Therefore, according to the mining conditions and the characteristics of coal seam of the upper Jurassic coal strata of Tongxin coal mine, the load-bearing characteristics of established gob coal pillars can be analysed as shown in Fig. 5.

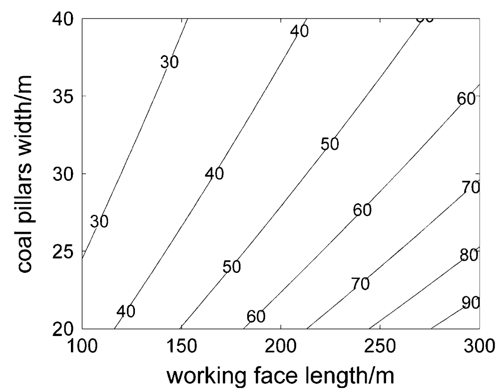
It is clear from Fig. 5a that if the length of working face is in the inclined direction, the established load of rock-overlaid strata and characteristics of coal pillars are fixed, and the load on the gob coal pillars is significantly affected by coal pillar dimensions. For coal pillars similar dimensions, a variation in the load carried associated with varying coal strata thickness at the working face was not evident. When the coal pillar size in the goaf is fixed, an increase in coal seam thickness caused the coal pillar to be "thin and tall" so as to increase the load on the coal pillar. Additionally, enlargement of the balanced arch structure in the goaf reduced the weight of the "pier-type" roof structure above the coal pillar, thereby reducing the load on the coal pillar; as such, the combined effect resulted in an insignificant effect of varying coal seam thickness on the load on the coal pillar. In contrary, for the same thickness of coal strata, the carried load increased with a decrease in the reserved width of the coal pillar.

Similarly, it is evident from Fig. 5b that when coal strata thickness, the established load of rock-overlaid strata and the coal pillar characteristics are fixed, and the reserved dimensions of gob coal pillars were identical, the carried load increased significantly with an increase in the length of the working face in the inclined direction; the gradient of increase was even.



l_t=150m; q_y=5.4MPa; φ=37°; η=1.0

(a) Effect of thickness of coal seam and width of coal pillars



h_m=3.5m; q_y=5.4MPa; φ=37°; η=1.0

(b) Effect of the length of working face and width of coal pillars

Fig. 5 Contour graph of gob coal pillar load

It is therefore obvious that when coal strata conditons are established, the carried load of established gob coal pillars is affected by the arranged length of the working face in the inclined direction and the reserved width of the coal pillars; the smaller the working face length in the inclined direction, the larger the reserved coal pillar dimensions, and the less load the established coal pillars carry.

Considering that the strength of coal pillars is relatively low and that they are not confined, when subjected to high stress imposed by rock-overlaid strata, the coal pillar will undergo complex elasto-plastic deformation or damage internally. This results in different load-bearing characteristics in different regions of the coal pillar (Liu et al. 2007; Xie et al. 2006). Normally, the coal pillar is in a biaxial loading state at the side closer to the gob, in which case plastic deformation or local damage is likely to occur, and the load-bearing capacity is relatively low; the stress in the coal body is transferred to the inner side of the coal pillar from the edge of coal pillar to the inside, the uniaxial stress state of the coal body shifts gradually to tri-axial stress state and the load-bearing capacity is improved.

In the elastic core region of the coal pillar, the boundary effect of the coal pillar is relatively small and the load-bearing capacity of the coal body in that region is stable. Based on the aforementioned characteristics of loading and deformation, the load in the established gob coal pillars is trapezoidal, as shown in Fig. 6.

In Fig. 6, q_m is the trapezoidal load of the coal pillars, l_p is the length of elastic core of the coal pillars and l_s is the length of stress reduction region of the coal pillars. From the perspective of a macroscopic force equivalent to the coal pillars, the trapezoidal load of gob coal pillars can be calculated as:

$$q_m = \frac{2ql_m}{l_m + l_p} \tag{8}$$

According to Eq. (8) and considering the condition of established gob coal pillars of Jurassic coal strata in the Tongxin coal mine, the relationship between the trapezoidal load on the coal pillars and the dimensions of the elastic core is shown in Fig. 7.

It is evident from Fig. 7 that the trapezoidal load borne by the coal pillars is reduced with an increased coal pillar width and elastic core. Therefore, larger coal pillars and a greater load-bearing rangehelps reduce the trapezoidal load on the coal pillars.

Analysis of the effect of stress of gob coal pillars

Considering that the strata between the Jurassic and carbonic coal strata are both sandy rock strata and the lithological characters of the roof are similar, elastic half-space theory was used to analyze the stress in the strata below the load-bearing coal pillars. The stress in the rock strata under linear triangular loading can be calculated as (Yang et al. 2014):

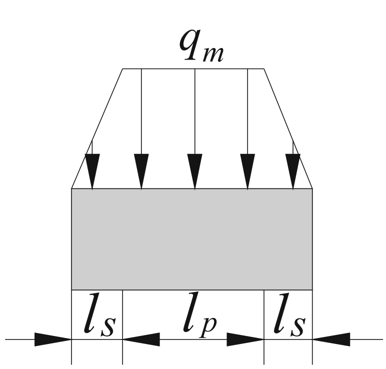


Fig. 6 Trapezoidal load of the coal pillars. l_t = 150 m, h_m = 3.5 m, q_y = 5.4 MPa, φ = 37°, η = 1.0

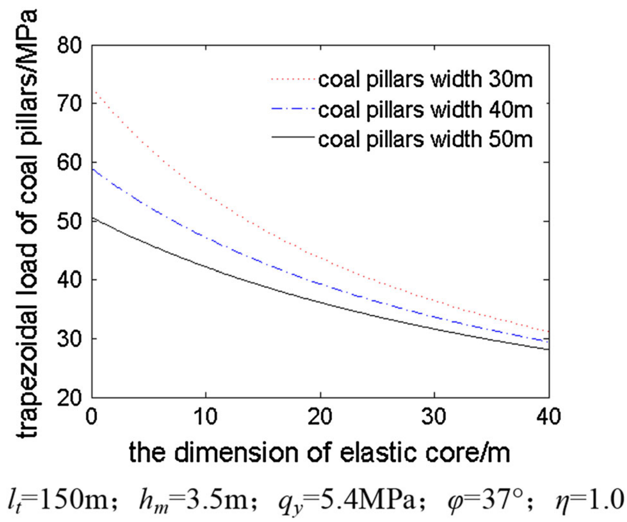


Fig. 7 Relationship of trapezoidal load on the coal pillars and the dimensions of the elastic core

$$\begin{cases} \sigma_{1xx} = q_c[(\theta_2 - \theta_1)\sin\theta_2 - \sin\theta_1 \sin(\theta_2 - \theta_1)] \\ \sigma_{1yy} = q_c[(\theta_2 - \theta_1)\sin\theta_2 + \sin\theta_1 \sin(\theta_2 - \theta_1) \\ \qquad -2\cos\theta_2 \ln(|\cos\theta_1|/|\cos\theta_2|)] \\ \sigma_{1xy} = q_c[\sin\theta_2 - \sin\theta_1 \cos(\theta_2 - \theta_1) \\ \qquad -(\theta_2 - \theta_1)\cos\theta_2] \end{cases} \tag{9}$$

In which

$$q_c = -\frac{k}{\pi}\frac{(a-b)\cos\theta_1}{\sin(\theta_2 - \theta_1)},$$

$$\theta_1 = \arctan\frac{y_A - a}{x_A},\ \theta_2 = \arctan\frac{y_A - b}{x_A}$$

where: σ_{1xx}, σ_{1yy}, σ_{1xy} are, respectively, stress components of rock strata under a pure triangular coal pillar loading condition; q_c is the load constant; x_A, y_A are, respectively, the vertical and horizontal coordinates of stress point A of the rock strata; θ_1, and θ_2 are the angles between stress point A and the two boundaries of the coal pillar; a and b are the distance from the origin to the right and left boundaries of the coal pillar, respectively; and k is a load factor.

The stress in the rock strata under an evenly distributed load can be solved as (Yang et al. 2012; Xu 2006):

$$\begin{cases} \sigma_{2xx} = -\frac{kb+\beta}{2\pi}[2(\theta_2 - \theta_1) + (\sin 2\theta_2 - \sin 2\theta_1)] \\ \sigma_{2yy} = -\frac{kb+\beta}{2\pi}[2(\theta_2 - \theta_1) - (\sin 2\theta_2 - \sin 2\theta_1)] \\ \sigma_{2xy} = \frac{kb+\beta}{2\pi}(\cos 2\theta_2 - \cos 2\theta_1) \end{cases} \tag{10}$$

where: σ_{2xx}, σ_{2yy}, σ_{2xy} are stress components of rock strata under an evenly distributed coal pillar load; and β is a load constant.

Considering Eqs. (9) and (10) simultaneously, the stress in the rock strata under a linear coal pillar loading condition can be calculated as:

$$\begin{cases} \sigma_{xx} = \sigma_{1xx} + \sigma_{2xx} \\ \sigma_{yy} = \sigma_{1yy} + \sigma_{2yy} \\ \sigma_{xy} = \sigma_{1xy} + \sigma_{2xy} \end{cases} \quad (11)$$

Analysis of application

After mining of Jurassic coal strata in the Tongxin mine, the falling rocks in the gobs and the natural arch structure of the rock-overlaid roof were in equilibrium due to long-term movement and adjustment. At this stage, the balanced arch in the gobs had a certain degree of load-bearing capacity, and continued to sustain the stability of the rock-overlaid strata loading in the form of a multi-gob, pier-type roof structure. The self-weight of falling rocks in the gobs acts directly on the flooring of the gobs in the coal strata and the load incurred is relatively small. Bearing in mind the the Jurassic coal strata in the Tongxin coal mine, the force model of lower-flooring rock strata under multi-gob coal pillars with a rock-overlaid roof is established as shown in Fig. 8.

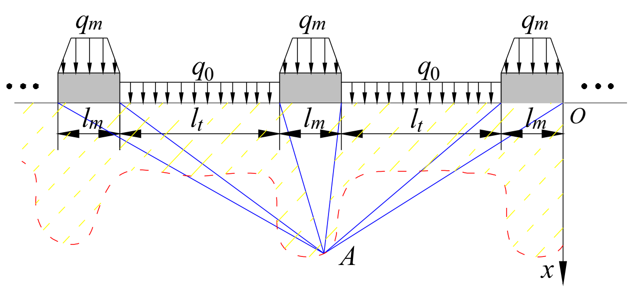


Fig. 8 Force analysis of rock-flooring strata under multi-gob coal pillars

In Fig. 8, q_0 is the load of falling rocks in the gobs on the floor. According to the occurrence of Jurassic coal strata in the Datong mine field, the length of a Jurassic coal working face has an average value of 150 m and the coal pillar width is 40 m; the collapsing height was 121 m as calculated by Eq. (3) and, thus, the load applied by falling rocks on the flooring was approximately 3.1 MPa. Considering the condition that the coal seam and roof strata was relatively hard, the length of the stress reduction region in both sides of the coal pillars was taken as 5 m, according to the measured results, and the length of coal pillar elastic core was 30 m. Therefore, considering Eqs. (6), (7), (8), (9), (10) and (11), the stress and energy

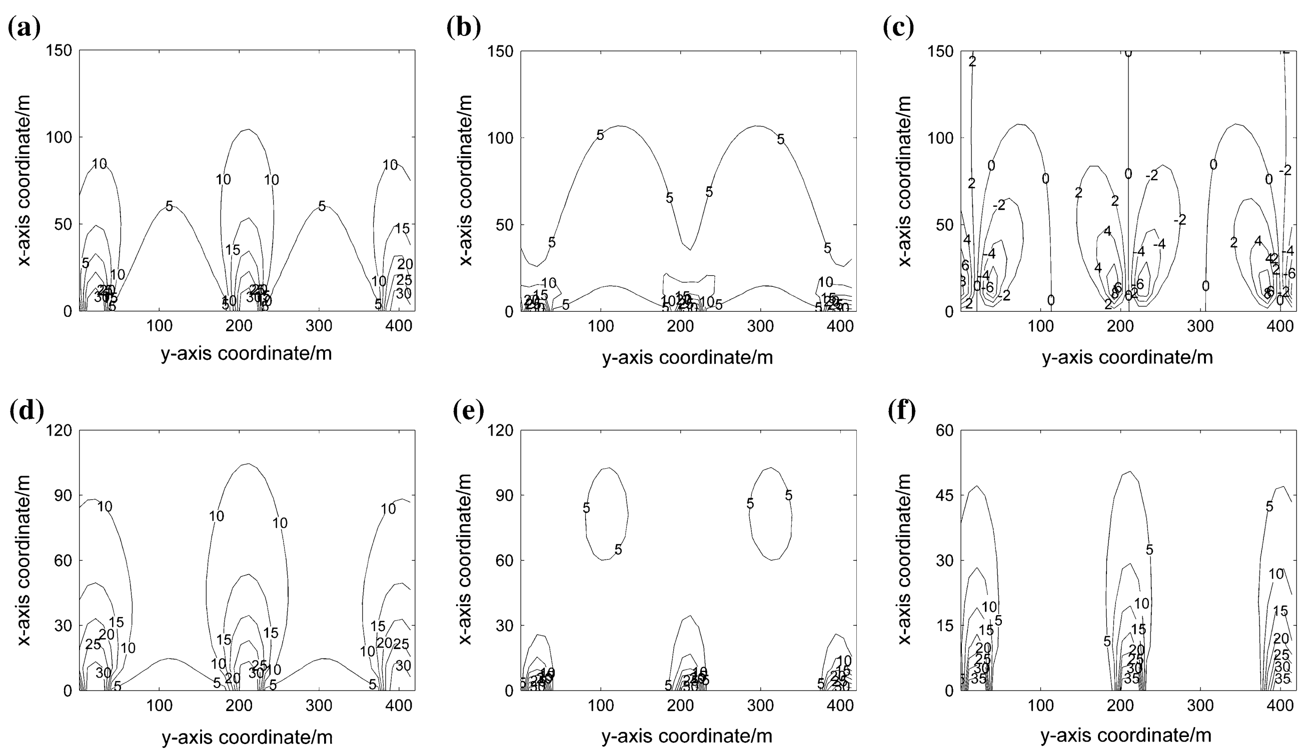


Fig. 9 Stress and energy density distribution of flooring rock strata affected by multi-gob established coal pillars with a rock-overlaid strata roof. **a** Vertical stress distribution (MPa); **b** horizontal stress distribution (MPa); **c** sheer stress distribution (MPa); **d** maximum principle stress (MPa); **e** minimum principle stress (MPa); **f** energy density of rock strata (kPa)

distribution of rock strata under multi-gob established coal pillars with a rock-overlaid strata roof are shown in Fig. 9.

It is evident from Fig. 9 that a pier-type roof structure with rock-overlaid strata resulted in stress concentration in lower rock strata under established gob coal pillars. Results from the calculation showed that the area of rock strata under the gob coal pillars affected by stress concentration had a depth of 100 m, and the area of lower rock strata affected by the energy density concentration had a depth of 50 m. Given that that the distance between Jurassic and carbonic coal strata in the Datong mine field is 200 m, it is obvious that, when comparing with overlying strata, the established gob coal pillars do not affect mining of the lower carbonic, extra-thick coal strata. However, when movement of the overlying rock due to mining of lower coal strata affects the area of stress concentration of the upper coal pillars (Yu et al. 2014), the concentrated elastic energy accumulated in the overlying rock will be released and the original balanced roof structure in the Jurassic coal strata will be reactivated, the combination of which will impose a significant effect on the mining of lower coal strata.

Conclusions

Based on the structural characteristics of the natural arch roof in the gobs inclined with the working faces of sub-horizontal coal strata, the upper roof of gob coal pillars in the Datong mine field was presented as a pier-type structure.

The natural arch roof in the gobs of Jurassic coal strata use the established coal pillars as a supporting arch springing; the concentrated load on the established coal pillars mainly comes from the weight of the pier-type roof strata and the overlying load. The magnitude of the load is affected by the length of the working face and dimensions of the established gob coal pillars.

A method for calculating stress in the lower rock strata was proposed in this study when the established gob coal pillars are subjected to any form of loading when the lithological character of the roof strata is similar. Considering the Jurassic coal strata in the Datong coal mine, the area of rock strata under the gob coal pillars affected by stress concentration has a depth of 100 m, and the area of lower rock strata affected by energy density concentration has a depth of 50 m.

Acknowledgments Financial support for this work was provided by the NSFC program (No. 51174192), the Innovation Project of Graduate Students Training of Jiangsu Province (No. CXLX12_0964), and the "333" Training Foundation of Jiangsu Province (No. BRA2010024).

References

Du XL, Song HW, Chen J (2011) Numerical simulation of the evolution of the pressure arch during coal mining. J China Univ Min Technol 6:863–867

Gao MS, Dou LM, Zhang N, Zheng BS, Kan JG (2005) Cusp catastrophic model for instability of coal pillar burst damage and analysis of its application. J China Univ Min Technol 4:433–437

Liu BC, Shen HQ (1988) The mathematical model and solution for optimization of coal pillar for preventing building. J China Coal Soc 3:18–25

Liu CY, Huang BX, Meng XJ (2007) Research on abutment pressure distribution law of over length isolated fully-mechanized top coal caving face. Chin J Rock Mech Eng 1:2671–2676

Miao XX (1990) Natural balance arch and the surrounding rock stability. Ground Press Strat Control 2:55–57

Qian MG, Miao XX, He FL (1994) Analysis of key blocks in the structure of voussoir in longwall mining. J China Coal Soc 6:557–563

Wang B, He KQ (2006) Study on limit equilibrium height expression of critical soil cave of karst collapse. Rock Soil Mech 3:458–462

Wang WJ, Hou CJ (2003) Stability analysis of coal pillar and immediate bottom of extraction opening. Rock Soil Mech 1:75–78

Wang JA, Zhao ZH, Hou ZY (2007) Study on the catastrophic collapse of surface land induced by mining under a shallow and hard strata. J China Coal Soc 10:1051–1056

Xie GX, Yang K, Liu QM (2006) Study on distribution laws of stress in inclined coal pillar for fully-mechanized top-coal caving face. Chin J Rock Mech Eng 3:545–549

Xu ZL (2006) Elastic mechanics. Higher Education Press, Beijing

Yang W, Liu CY, Huang BX, Yang Y (2012) Determination on reasonable malposition of combined mining in close-distance coal seams. J Min Saf Eng 1:101–105

Yang JX, Liu CY, Yang Y, Li JW (2013) Study of the bearing mechanism of the coal roof and the dimension selection of the room and pillar in the shallow and close distance coal seam. J China Univ Min Technol 2:161–168

Yang JX, Liu CY, Yu B (2014) Mechanism of intense strata behaviors at working face influenced by gob pillars of overlying coal seam. Disaster Adv 4:27–35

Yu B, Liu CY, Yang JX, Liu JR (2014) Mechanism of strong pressure reveal under the influence of mining dual system of coal pillar in Datong mining area. J China Coal Soc 1:40–46