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TECHNICAL ARTICLE

A Proposed Method of Coal Pillar Design, Goaf Filling, and Grouting of Steeply Inclined Coal Seams Under Water-Filled Strata

C. Y. Liu · J. X. Yang · F. F. Wu

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Abstract The key to safely and efficiently mining steeply inclined coal seams under water-filled strata is to size barrier pillars appropriately and to control the structural integrity of the roof. We propose a method for goaf filling and grouting of steeply inclined coal seams and for appropriately sizing barrier and sectional coal pillars for mining in such conditions. Through theoretical analysis, an expression for a reasonable barrier pillar size was derived, based on the time span of mining, the hydraulic characteristics of the coal seam, the permeability characteristic of the grout in the goaf, and the water pressure. Based on the degree of saturation of the overlying strata and the mining conditions of the steeply inclined no. 48 coal seam of the Longhu mine in Qitaihe, China, we determined through theoretical analysis that the barrier pillar should be 80 m, the width of the sectional coal pillar should be 15 m, the length of the goaf filling should be 80 m, and the grouting length should be 40 m, to ensure safe production in that mine without geotechnical failures or injuries. These recommendations are being implemented.

Keywords Goaf grouting · Mining duration · Seepage time · Longhu mine

Introduction

Steeply inclined coal seams account for about 4 % of China's total reserves of coal; 80 % of these steeply inclined coal seams exist in southern China, while a few are distributed in northeast and central China (Xie et al. 2007). The goaf formed by the mining of shallow coal seams is often saturated with water due to communication with rivers on the earth's surface. When lower coal seams are mined, the overlying water-filled strata can cause huge potential safety problems at the working face (Du and Wang 2005). Therefore, when a steeply inclined coal seam is mined under such conditions, barrier pillars must be designed to ensure safe mining, while minimizing coal loss.

Various analytical methods have been developed to determine the appropriate size of barrier and longwall coal pillars for different coal seam conditions (Gale 1996; Gui 1997; Jia et al. 2009; Mark 1992; Tang et al. 2006; Wu et al. 2004), such as when: the exit of key stratum in a steep seam can enlarge the falling range of a pillar, allowing water to more easily to enter the goaf (Li et al. 2012); the coal pillar obviously cannot reduce the height of a permeable fractured zone, and the pillar is subject to plastic failure, which would allow the fracture to connect with an aquifer (Liu et al. 2010); high content of clay minerals will result in weak permeability and regenerated water tightness, and the effective height of water flowing-fractured zone aligns with the caving zone height of overlying strata (Tu et al. 2004). In addition, a method for coal pillar design was developed based on the division of "elastic–plastic-failure" coal pillar zones (Li 2012; Liu and Ding 2001), an empirical method was derived from experience (State Bureau of Coal Industry 2000), and methods have been developed to design pillar layouts for potential variability in strata strength characteristics surrounding a coal seam (Gale 1998). In this paper, we propose a method to define coal pillar design, goaf filling, and grouting for mining a steeply inclined coal seam under overlying strata that

C. Y. Liu · J. X. Yang (✉) · F. F. Wu
State Key Laboratory of Coal Resources and Safe Mining, Key Laboratory of Deep Coal Resource Mining Ministry of Education, School of Mines, China Univ of Mining and Technology, Xuzhou 221116, Jiangsu, China
e-mail: jxyangcumt@126.com

contains water, to prevent seepage and ensure safe production in a mine that engages in blasting.

Theoretical Analysis

Analysis of the Appropriate Size of the Barrier Pillar

Up-dip longwall mining has been used to mine steeply inclined thin and moderately thick coal seams (Howard and Hartman 1992; Xu 2004). The working face for such mining is illustrated in Fig. 1.

Water from overlying strata gradually flows towards the working face and goaf through the barrier pillar (Aston et al. 1983; Doulati Ardejani et al. 2003; Fawcett et al. 1984; Singh and Atkins 1984). Therefore, assuming that the roof strata are stable, the size of the barrier pillar should be large enough to guarantee that water from overlying strata takes longer to flow through the barrier pillar than it takes to mine the coal seam. Calculating uniform seepage of water from overlying strata into the barrier pillar uses the interface equation for seepage inside a coal pillar:

$$l = l(t) \tag{1}$$

where l is the location of the seepage interface from the overlying strata in the barrier pillar (the initial location is the interface between the water from the overlying strata and the barrier pillar); t is the seepage time from overlying strata, and $l(t)$ is a function of the location of the seepage interface from overlying strata in the barrier pillar. By assuming that the barrier pillar is only affected by hydrostatic seepage of water, a barrier pillar seepage model for a steeply inclined coal seam was established. The selected coordinates of the barrier pillar's x axis are shown as Fig. 2.

Thus, the obtained equation for the seepage of water from overlying strata in the coal pillar and the corresponding boundary conditions are:

$$\begin{cases} \dfrac{\partial^2 p_1}{\partial x^2} = 0 \quad [0 \le x \le l(t)] \\ \dfrac{\partial^2 p_2}{\partial x^2} = 0 \quad [l(t) < x \le l_1] \\ p_1 = p_w \quad (x = 0) \\ p_2 = p_c \quad (x = l_1) \end{cases} \tag{2}$$

where p_1 is the pore water pressure of the coal pillar through which the water from overlying strata seeps; p_2 is the pore water pressure of the coal pillar without the seepage of the water from overlying strata; p_w is the hydrostatic pressure at the interface between the water from overlying strata and the coal pillar; p_c is the pore water pressure on the sidewall of the barrier pillar roadway, and; l_1 is the size of the barrier pillar. Considering the pore water pressure at the seepage interface in the coal pillar and the conditions for flow continuity, we obtained:

$$\begin{cases} p_1 = p_2 \\ \dfrac{K_1}{\mu_1}\dfrac{\partial p_1}{\partial x} = \dfrac{K_2}{\mu_2}\dfrac{\partial p_2}{\partial x} = -\dfrac{Q(x)}{A} \end{cases} \tag{3}$$

where K_1 and K_2 are the permeabilities on both sides of the seepage interface in the coal pillar; μ_1 and μ_2 are the fluid viscosities on both sides of the seepage interface; $Q(x)$ is the flow of water from overlying strata through the seepage interface, and A is the cross-sectional area of the seepage interface. Then, the pore water pressure in the barrier pillar can be determined by combining Eqs. (1) and (2), and the first part of Eq. (3):

$$\begin{cases} p_1(x) = p_w - \dfrac{p_w - p_c}{(1-M)l(t) + Ml_1}x \\ p_2(x) = p_c + \dfrac{p_w - p_c}{(1-M)l(t) + Ml_1}M(l_1 - x) \end{cases} \tag{4}$$

where $M = (K_1\mu_2)/(K_2\mu_1)$ and M is the mobility ratio. By incorporating Eq. (4) into Eq. (3), we determined that the

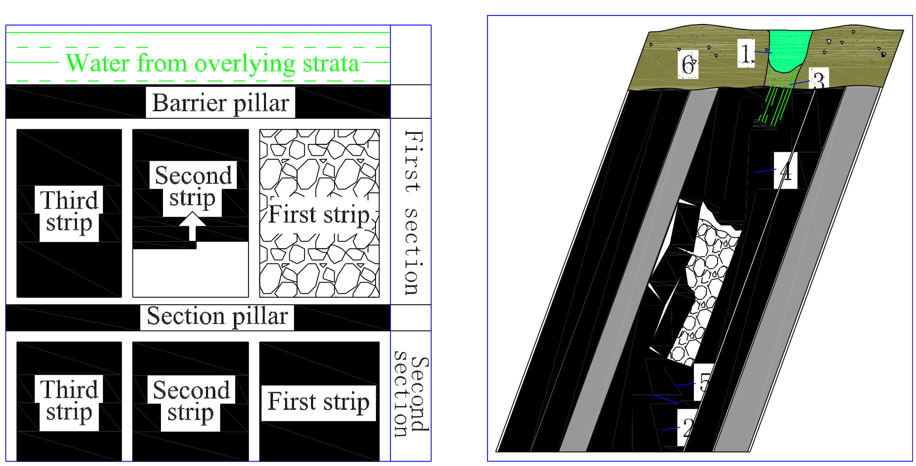

Fig. 1 The plan and cross-section of coal mining in steeply inclined strata that contain water; *1* water from overlying strata; *2* coal seam; *3* water-conducting fracture; *4* barrier pillar; *5* section coal pillar; *6* epipedon

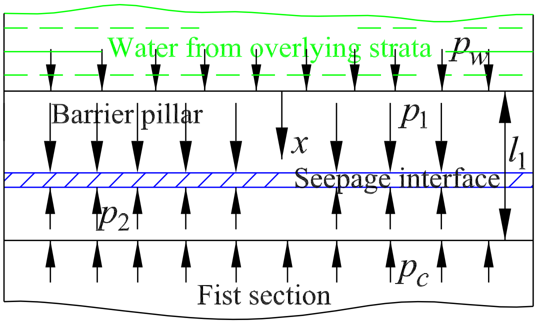

Fig. 2 The seepage model of the barrier pillar

seepage discharge of water from overlying strata in the barrier pillar is:

$$Q(x) = \frac{AK_1}{\mu_1}\frac{p_w - p_c}{Ml_1 + (1-M)l(t)} \tag{5}$$

Then, by combining the differential relationship formula of the seepage water velocity from overlying strata in the coal pillar and the physical definition formula of seepage velocity, we obtained the following equation:

$$v = \frac{dl}{dt} = \frac{Q}{A_e} = \frac{Q}{A\phi_1} \tag{6}$$

where v is the flow velocity at the seepage interface; A_e is the effective cross-sectional area of seepage; A is the actual cross-sectional area of seepage, and φ_1 is the porosity of the barrier pillar.

By combining Eqs. (5) and (6), we obtained the following differential relationship expression:

$$\frac{dl}{dt} = \frac{K_1}{\phi_1\mu_1}\frac{p_w - p_c}{Ml_1 + (1-M)l(t)} \tag{7}$$

By solving the integral of the differential relationship formula (7), the time t_{l1} for the seepage interface in the coal pillar to go from $x = 0$ to $x = l$ becomes:

$$t_{l1} = \frac{\phi_1\mu_1 l_1^2}{K_1(p_w - p_c)}\left[\frac{Ml}{l_1} + \frac{1}{2}(1-M)\left(\frac{l}{l_1}\right)^2\right] \tag{8}$$

It can be seen from Eq. (8) that the time, t_z, required for water to seep from overlying strata through the entire barrier pillar is:

$$t_z = \frac{\phi_1\mu_1 l_1^2(1+M)}{2K_1(p_w - p_c)} \tag{9}$$

where t_z is the time for water to seep from overlying strata through the barrier pillar.

It can be seen that the time for water to seep from overlying strata through the barrier pillar is also affected by the static pore water pressure on both sides of the interface of the coal pillar and the size of the coal pillar, in addition to the hydraulic properties of the coal seam (porosity, the permeabilities, and fluid viscosities before and after seepage through the coal pillar). Therefore, in order to ensure safe production at the working face during mining of a steeply inclined coal seam, in addition to relevant measures taken to reduce the seepage properties of the coal pillar, appropriate barrier pillar sizing becomes critical. The size of the coal pillar should guarantee that the pillar is not affected by seepage of water from overlying strata during mining, namely $t_{m1} \le t_z$, where t_{m1} is the mining duration in the first section of the coal seam.

In order to ensure safe mining in the first panel of the coal seam, the size of the barrier pillar of the steeply inclined coal seam should, in combination with Eq. (9), meet:

$$l_1 \ge \sqrt{\frac{2K_1(p_w - p_c)t_{m1}}{\phi_1\mu_1(1+M)}} \tag{10}$$

Simultaneous Mining, Filling, and Grouting of the Steeply Inclined Coal Seam

During mining of the first panel, effective goaf filling and grouting will improve roof control and barrier pillar effectiveness and help ensure safe and efficient mining of the coal seam in the lower sections. Therefore, it was proposed that gangue be filled and grouted in the goaf of the first panel during stoping of the second panel. This simultaneous mining, filling, and grouting of the steeply inclined coal seam is illustrated (Fig. 3).

Filling and grouting gangue in the goaf of the steeply inclined coal seam has advantages:

1. adding gangue to the goaf of the steeply inclined coal seam can effectively reduce roof collapse and the tendency of fractures in the roof to expand upward and conduct overlying water.

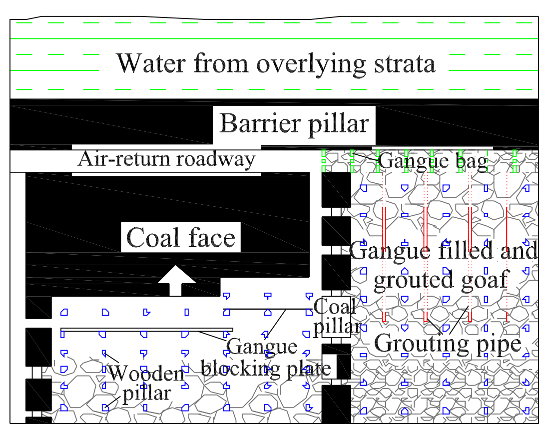

Fig. 3 The simultaneous operation system of mining, filling and grouting of the coal seam

2. grouting of the gangue placed in the goaf can enhance the overall bearing capacity of the gangue so as to effectively support and control the roof, reduce the force applied to the barrier pillar, and ensure the effectiveness of the coal pillar design.
3. consolidation of the grouted material significantly reduces the permeability of the goaf, thereby increasing the seepage time of water from overlying strata, and ensure normal and safe stoping at the working face of the coal seam in the lower panels.
4. filling and grouting gangue in the goaf reduces the seepage rate in the goaf and thereby reduces the required size of the pillars between sections of the steeply inclined coal seam.

Analysis of the Size of the Section Coal Pillars, Goaf Filling, and Grouting

Grouting parameters can be changed to improve the grout flow rate and increase the grout's capacity to reduce the permeability of the goaf, increase the time before water seeps from the overlying strata into the coal seam, and provide a way to safely reduce the size of the coal pillars and increase the recovery ratio. A relationship between the size of the section coal pillar of the steeply inclined coal seam and the technological parameters of goaf grouting, a seepage model for safe coal seam mining under multi-zone conditions was established (Fig. 4).

Unlike the previous analysis, the pore water pressure on the sidewall of the barrier pillar roadway of the coal seam in the first section is no longer p_c and should be replaced by the new pore water pressure at the interface p_{c1}. According to the conditions for the flow continuity at the interface of multiple zones, we obtain the following relationship:

$$\begin{cases} \dfrac{K_1}{\mu_1}\dfrac{p_w - p_{c1}}{l_1} = \dfrac{K_3}{\mu_3}\dfrac{p_{c1} - p_{c2}}{M_1 l_2} \\ \dfrac{K_3}{\mu_3}\dfrac{p_{c1} - p_{c2}}{l_2} = \dfrac{K_5}{\mu_5}\dfrac{p_{c2} - p_c}{M_2 l_3} \end{cases} \tag{11}$$

where p_{c1} and p_{c2} are the pore water pressure at the interface of multiple zones; p_c is the pore water pressure on the sidewall of the section coal pillar roadway; l_2 is the goaf grouting length; l_3 is the size of the section coal pillar, and M_1 is the mobility ratio of the filled and grouted goaf. $M_1 = (K_3\mu_4)/(K_4\mu_3)$, where K_3 and K_4 are the permeabilities on both sides of the seepage interface in the filled and grouted goaf and μ_3 and μ_4 are the fluid viscosities on both sides of the seepage interface in the goaf. Similarly, M_2 is the mobility ratio in the section coal pillar and $M_2 = (K_5\mu_6)/(K_6\mu_5)$, where K_5 and K_6 are the permeabilities on both sides of the seepage interface in the section coal pillar and μ_5 and μ_6 are the fluid viscosities on both sides of the seepage interface in the section coal pillar.

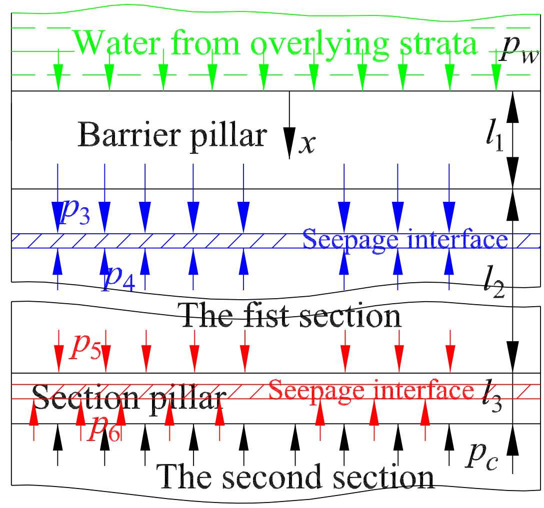

Fig. 4 The section coal pillar design and goaf grouting model

By solving Eq. (11), we can see that pore water pressure at the interface of multiple zones is:

$$\begin{cases} p_{c1} = \dfrac{\mu_4 K_1(\mu_3 K_6 l_2 + \mu_6 K_3 l_3)p_w + \mu_1\mu_3 K_4 K_6 l_1 p_c}{\mu_1\mu_3 K_4 K_6 l_1 + \mu_3\mu_4 K_1 K_6 l_2 + \mu_4\mu_6 K_1 K_3 l_3} \\ p_{c2} = \dfrac{\mu_3\mu_6 l_2 l_3}{\mu_3 K_6 l_2 + \mu_6 K_3 l_3}\left(\dfrac{K_3}{\mu_3 l_2}p_{c1} + \dfrac{K_6}{\mu_6 l_3}p_c\right) \end{cases} \tag{12}$$

By referring to the conclusion obtained from Eq. (10), we can see that the total seepage time of multiple zones and the conditions for safe mining of the second section of the coal seam are respectively:

$$\begin{cases} t_{z1} = \dfrac{\phi_1\mu_1 l_1^2(1+M)}{2K_1(p_w - p_{c1})},\ t_{z2} = \dfrac{\phi_2\mu_3 l_2^2(1+M_1)}{2K_3(p_{c1} - p_{c2})} \\ t_{z3} = \dfrac{\phi_3\mu_5 l_3^2(1+M_2)}{2K_5(p_{c2} - p_c)},\ t_{z1} + t_{z2} + t_{z3} \geq t_{m1} + t_{m2} \end{cases} \tag{13}$$

where t_{z1}, t_{z2}, and t_{z3} are, respectively, the time for the seepage through the barrier pillar, the filled, and grouted goaf, and the section coal pillar; φ_2 and φ_3 are, respectively, the porosities of the filled and grouted goaf and the section coal pillar, and t_{m2} is the mining duration of the coal seam in the second section.

By combining Eqs. (12) and (13), we can obtain the relationship between the size of the section coal pillar of the steeply inclined coal seam and the technological parameters of the goaf grouting to provide a theoretical basis for determining the required sectional coal pillar size and optimizing the technological parameters of goaf filling and grouting. Based on this analysis, determination of the appropriate coal pillar size and the filling and grouting should obey the following principles:

1. The barrier pillar size should be determined to ensure safe mining of the first section of the steeply inclined coal seam;
2. reasonable technological parameters of goaf filling and grouting should be determined to improve the bonding strength and compactness of the gangue in the goaf, reduce the size of the section coal pillar, and improve the recovery ratio; and
3. the sequence of coal mining, goaf filling, and grouting should be reasonably arranged in terms of time and space.

Engineering Applications

The Conditions of the Coal Seams

The Longhu coal mine in Qitaihe of Heilongjiang, China has steeply inclined coal seams, including the no. 44, 46, 48, 54, 57, 58, and 59 coal seams. The dip angles of the coal seams average 60° and the maximum dip angle is 73°. The coal seams are 0.6–1.3 m thick and have low hardness. The roof and the floor are 93–97 % sandy formations and are relatively stable. There are three abandoned mines in the area that have been depleted and the South no. 2 mining area is located both under their goaf and above it. The minimum elevation to be mined is −50 m. There is water in the area and the immediate roof of the coal seam is mainly siltstone and medium-grained sandstone, with a relatively high hardness; the uniaxial compressive strength of the roof rock strata exceeds 70 MPa.

The barrier pillar design, goaf filling, and grouting of the steeply inclined coal seam were analyzed for mining of the no. 48 coal seam, which is, on average, 0.7 m thick, with a dip angle of 63°. The roof and floor of the coal seam are hard sandstone with a dip length of 80 m and a strike length of 25 m. The first coalface will be mined by blasting. A 5 m coal pillar was designed between the adjacent panel working faces. The geology of the no. 48 coal seam in the South no. 2 area is shown (Fig. 5).

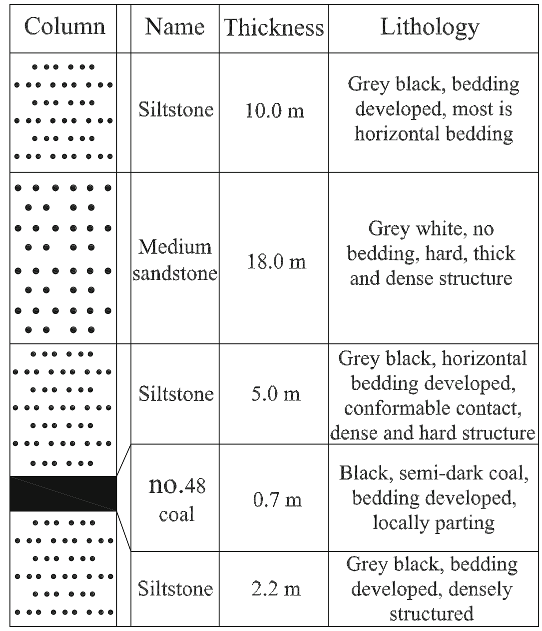

Fig. 5 The overall histogram of the no. 48 coal seam in the South no. 2 mining area of Longhu

Determining the Appropriate Barrier Pillar Size

The steeply inclined no. 48 seam in the South no. 2 mining area of the Longhu coal mine receives a reduced downward force applied by the roof (Table 1), so it has a relatively intact structure with a relatively low porosity and permeability. The measured permeability, K_1, of the coal is 7.58×10^{-3} μm^2 poor (Table 2; Yu 2009) and the porosity of the coal seam is 0.18. Considering the small change in the permeability characteristics on both sides of the seepage interface of the coal seam, we set the mobility ratio, M, as 1 (Kong 2010) and the fluid viscosity of the pore water in the coal seam, μ_1, as 1.31×10^{-3} Pa s (Kong 2010; Lei 1993). The pore water pressure p_c on the sidewall of the barrier pillar roadway is zero.

The corresponding relationship between the barrier pillar size and the water pressure from overlying strata on the upper boundary of the coal pillar can be calculated for different mining durations of the first panel using Eq. (10). Figure 6 shows that for a defined mining duration, the barrier pillar size increases as the water pressure from overlying strata on the upper boundary of the coal pillar increases, and that the rate of increase in the coal pillar size gradually stabilizes as water pressure from overlying strata increases. Given the hydrological conditions, when the static water pressure from overlying strata on the upper boundary of the barrier pillar is 3.2 MPa, the required coal pillar size is about 58 m for a mining duration in the first section of 1 year; the coal pillar size should be about 80 m when the mining duration in the section is 2 years, etc. Therefore, properly accelerating the mining of the steeply inclined coal seam so as to reduce the duration of mining can reduce the required barrier pillar size and thereby increase the recovery ratio. However, in view of the complex conditions, the appropriate barrier pillar size in the first section of the steeply inclined no. 48 coal seam required to ensure safe production was determined to be 80 m.

Determining the Section Coal Pillar Size and the Filling and Grouting Parameters

The porosity of a coal seam after goaf filling and grouting is greater than before mining. The porosity of the filled and

Table 1 Rock mechanical parameters of the no. 48 coal seam

Strata	Thickness/m	Density/ $\times 10^3$ kg m^{-3}	Bulk modulus/GPa	Shear modulus/MPa	Adhesion/MPa	Friction angle/°	Tensile strength/MPa
Siltstone	10.0	2.8	26	13	28	30	1.18
Medium sandstone	18.0	2.6	18	10	30	32	1.12
Siltstone	5.0	2.5	20	11	33	28	1.03
Coal seam	0.7	1.4	12	8	4	20	0.60
Siltstone	2.2	2.6	20	11	26	29	1.15

Table 2 The Chinese permeability criteria for coal

Level of permeability	Coal permeability				
	Very bad	Bad	General	Good	Very good
Permeability $K \times 10^{-3}/\mu m^2$	<1	1–10	10–100	100–500	>500

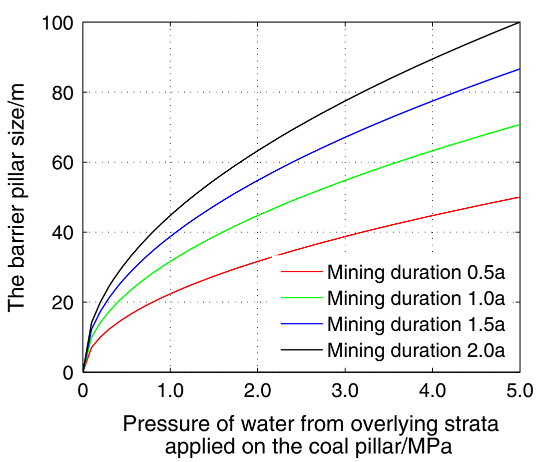

Fig. 6 The relationship between coal pillar design and water pressure from overlying strata under different mining durations of the first section of the coal seam

grouted goaf φ_2 is 0.35 (Miao et al. 2004), while the porosity of the section coal pillar φ_3 is still 0.18. For convenience, the fluid viscosities of pore water μ_1 to μ_6 were all set at 1.31 $\times$ 10^{-3} Pa s; the ratios of the mobilities on both sides of the seepage interfaces in the filled and grouted goaf and the section coal pillars M_1 and M_2 are both 1; and the permeability of the coal pillars K_1, K_5, and K_6 is 7.58 $\times$ 10^{-3} μm^2. The water pressure from overlying strata on the upper boundary of the barrier pillar is 3.2 MPa and the pore water pressure on the sidewall of the section coal pillar roadway should be zero. By combining Eqs. (12) and (13), we obtain a relationship between the section coal pillar size and the goaf grouting parameters for a steeply inclined coal seam under different permeabilities of the filled and grouted goaf (Fig. 7).

In Fig. 7, the thin line group represents the relationship between section coal pillar size and goaf filling and grouting lengths for a mining duration in the first section of 1 year and a total mining duration of the coal seam in two sections of 2.5 years. Under this condition, the coal barrier pillar size in the first section is 58 m. The thick line group represents the relationship between the same parameters when the mining duration of the coal seam in the first section is 2 years and the total mining duration of the coal seam in two sections is 4.5 years. Under this condition, the coal barrier pillar size in the first section is 80 m. Curves in different colors represent different degrees of goaf grouting. The red, green, blue, and black curves represent permeabilities of 15 $\times$ 10^{-3}, 35 $\times$ 10^{-3}, 55 $\times$ 10^{-3}, and 75 $\times$ 10^{-3} μm^2, respectively, for the goaf. These curves show that:

1. for a certain mining duration, properly increasing the gangue filling and grouting lengths of the goaf can effectively reduce the section coal pillar size and improve the recovery ratio.
2. for a certain mining duration, as the permeability of the filled and grouted goaf increases, the relationship between the section coal pillar size and the goaf filling and grouting lengths gradually stabilizes.
3. for a defined permeability of the coal, the goaf filling, grouting lengths, and the section coal pillar size should all increase as the coal seam is mined to ensure safe mining.
4. for different mining durations and the same permeability of the filled and grouted goaf, the curves for the relationship between the section coal pillar size and goaf filling and grouting lengths are basically parallel.

Figure 7 shows that when the goaf grouting length of the no. 48 coal seam is 40 m, the above conditions can be satisfied with sectional coal pillars less than 10 m $\times$ 10 m. However, considering the influence of mining of adjacent working faces on the coal pillar, to ensure the stability of

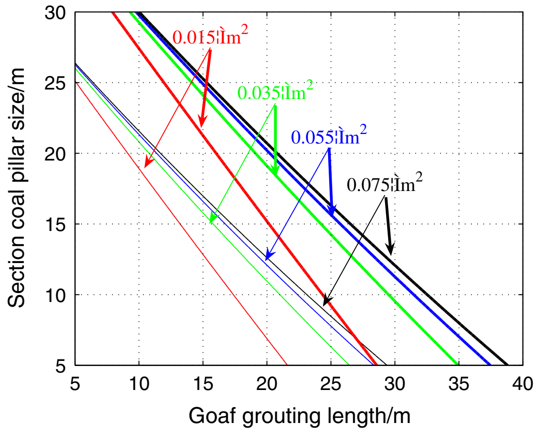

Fig. 7 The relationship between the section coal pillar size and grouting parameters under different goaf permeabilities

the coal pillar during mining of the lower panels and reduce goaf filling and grouting costs, the optimal section coal pillar size, goaf filling length, and grouting length was determined to be 15, 80, and 40 m, respectively.

Conclusions

First, with respect to water seepage from overlying strata, the barrier pillar size has to be large enough to ensure that the time required for water to seep through the barrier pillar is greater than the duration of mining in the first section of the coal seam. On this basis, a theoretical analysis can provide the necessary barrier pillar size.

Second, during mining of the steeply inclined coal seam under these conditions, goaf filling and grouting can effectively stabilize the working face roof, reduce the permeability of the filled and grouted goaf, prolong the seepage time of pore water in the goaf, and reduce the required dimensions of the section coal pillar from the experience-based value of 40 m previously adopted by the mine to a calculated value of 15 m.

Third, the section coal pillar size is also affected by the duration of mining in addition to the effects of goaf filling and grouting. Reducing mining time will help control water flow from overlying strata.

Fourth, according to hydrological and production conditions of the Longhu coal mine in Qitaihe, China, a barrier pillar dimension of 80 m, a section coal pillar dimension of 15 m, goaf filling length of 80 m, and a grouting length of 40 m should ensure the safe mining of adjacent coal faces.

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