Hydraulic flushing in soft coal sublayer: Gas extraction enhancement mechanism and field application

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Hydraulic flushing in soft coal sublayer: Gas extraction enhancement mechanism and field application

Abstract
In China, one or several ultrathin soft coal sublayers are widely developed in the coal seam. Therefore, a method of using hydraulic flushing in soft sublayer to enhance the gas extraction in these particular coal seams is developed in this work. We first established a new fully coupled gas extraction model by combing gas diffusion, gas flow, and a permeability model that considers the effect of stress change and plastic failure. By adopting this model, the gas extraction enhancement mechanism and its main influence factors were studied using the numerical simulation method based on the engineering and geological background in the Yangquan No.5 coalmine. Thereafter, a hydraulic flushing equipment, which could move freely in the underground coalmine, was developed to apply the hydraulic flushing method in soft coal sublayers used in the 8402 working face. Its gas extraction effect was systematically investigated. Our simulation results match well with the field results, suggesting that our model is feasible. Meanwhile, after adopting this method, the gas extraction condition in this coalmine improves significantly. The borehole number decreases by 66.7%, while the gas extraction rate and gas extraction concentration increase by 1.33 times and 3 times, respectively. Moreover, during the coal mining process, the gas adsorption index of drilling cuttings, the quantity of drilling cuttings, and the CH4 concentration also decrease dramatically.

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INTRODUCTION

China’s energy structure is characterized by rich coal reserve, and meager oil and gas reserves.\(^1\)–\(^7\) As a result, coal and coal-bed methane (CBM) play an important role in its energy supply.\(^8\)–\(^9\) However, most of the Chinese coal-bearing strata have undergone several tectonic movements after their formation. During this process, the original structure of the coal mass was damaged; as a result, the coal mass became soft, highly compacted, and impermeable for gas flow.\(^10\) In general, the permeability in the soft coal could be several orders of magnitude less than that in the hard coal.\(^7\) Therefore, its gas extraction is rather difficult, and thus, more than 20 thousand coal and gas outburst accidents have been reported in China in its coal mining history.\(^11\) This makes its coal mining industry the most outburst risk troubled sector in the world.\(^3\)–\(^4\),\(^12\)–\(^14\)
To enhance the gas extraction and thus eliminate the coal and gas outburst risk in the soft coal seam, hydraulic flushing/slotting technology has been widely adopted in China because of its low cost, high efficiency, high safety, and little environment pollution.\(^\text{15-22}\) The main principal of this technology is to wash out some coal mass by adopting the high-pressure water jet after the drilling of the borehole. During this process, plastic failure and stress unloading would occur in the surrounding coal mass; as a result, the permeability increases and the gas extraction condition improves.\(^\text{21}\) Due to the high gas extraction efficiency of this new technology, it has drawn great attention in the past few years. Yan et al.\(^\text{24}\) adopted the hydraulic fracturing technology to further improve the gas extraction efficiency of the hydraulic flushing borehole. Zou et al.\(^\text{7}\) developed a new drilling and flushing integrated bit and a new coal-water-gas separation instrument, which could significantly improve the hydraulic flushing efficiency. Yang et al.\(^\text{21}\) investigated the optimal coal discharge in the Pingmei coalfield. Meanwhile, the related theoretical studies have also been conducted in the literature from different perspectives. Lu et al.\(^\text{19}\), Yang et al.\(^\text{21}\) and Shen et al.\(^\text{23}\) studied the stress redistribution and plastic failure characteristics in the surrounding coal mass after hydraulic flushing by adopting the numerical simulation method. Gao et al.\(^\text{26}\) further analyzed the permeability evolution law and divided the surrounding coal mass into a permeability-increasing zone, a permeability-decreasing zone, and an initial permeability zone. Moreover, Kong et al.\(^\text{18}\), Gao et al.\(^\text{26}\) and Zhao et al.\(^\text{28}\) analyzed the gas flow characteristics of the hydraulic flushing/slotting borehole during the gas extraction process. However, there are four main shortcomings in the existing studies. Firstly, the above studies were based on the engineering and geological background that the whole coal seam is soft coal. In China, many soft coal mass only develops as one or several ultrathin sublayers in the coal seam. Lu et al.\(^\text{27}\) pointed out that this kind of coal seam is of greater coal and gas outburst risk due to the fact that uncoordinated horizontal deformation always occurs at the interface between the soft sublayer and the hard sublayer. However, little attention has been paid to the gas extraction in this special kind of coal seam. Secondly, the effect of plastic failure on the permeability evolution was not fully considered due to the lack of the permeability model in the postpeak stage. According to the previous research,\(^\text{29,30}\) the coal permeability could increase by several orders of magnitude during the plastic failure process. Therefore, neglecting the plastic failure will result in serious underestimate on the permeability evolution and thus the gas flow. Third, the current hydraulic flushing equipment is still required to be further improved due to the fact it is too heavy to move in the underground coalmine. The last but not least, the above researches were conducted based on a specific geostress field; the effect of geostress field on the gas extraction was not considered. Under different geostress field, the stress redistribution and the plastic failure pattern after hydraulic flushing could also be rather different.

Therefore, in this work, we proposed a new gas extraction method, hydraulic flushing in soft coal sublayer, to enhance the gas extraction in the coal seams that contain one or several ultrathin soft sublayers. Firstly, we established a fully coupled gas extraction model by combining gas diffusion, gas flow, and a permeability model that considers the effect of stress change and plastic failure. On this basis, the gas extraction enhancement mechanism of this new method was studied by adopting the numerical simulation method according to the engineering and geological background in the Yangquan No.5 coalmine. Thereafter, we analyzed the effects of flushing width and geostress field on the permeability evolution and thus the gas extraction. Finally, this new gas extraction method was applied in the Yangquan No.5 coalmine by adopting an improved hydraulic flushing equipment, and its gas extraction effect was systematically investigated.

## 2  |  GEOLOGICAL BACKGROUND AND TECHNOLOGY SYNOPSIS

### 2.1  |  Geological and engineering background

Yangquan coalfield with more than 30 active underground coalmines is located in northeastern Shanxi province, which is one of the major coal and CBM production bases in China (Figure 1A). Yangquan No.5 coalmine is located at the eastern Yangquan coalfield, covering an area of 82.53 km². In this coalmine, the No.15 coal seam with an average thickness of 6.2 m is the only one with commercial value (Figure 1B). After the formation of the coal-bearing stratum, it has experienced several strong tectonic movements, leading to the wide development of the fold structures. During this process, interformational sliding occurred in the coal seam along the weak face; as a result, a soft sublayer widely develops at the middle of the coal seam.

Moreover, collapse columns also widely develop in this coalmine. The collapse columns connect the No.15 coal seam and the earth’s surface, which forms the natural flow channels for the gas, resulting in a relatively low gas content (GC) in this coalmine. However, with the increase in the mining depth, the gas pressure and GC increase notably, and a serious coal and gas outburst accident has happened in 2014. The 8402 working face is located at the Fourth mining district of the Yangquan No.5 coalmine (Figure 1A). In this working face, the average thickness of the soft sublayer is 0.2 m (Figure 1A), and the field determined gas pressure is approximately 1.0 MPa. The GCs in the hard sublayer and the soft sublayer are 9.68 m³/t and 10.49 m³/t, respectively, which are much greater than their critical value (8 m³/t). Meanwhile, the firmness coefficient of the soft coal is just approximately...
0.2–0.3. Therefore, gas extraction measures must be taken to eliminate the outburst risk before mining. However, the permeability in the No.15 coal seam is rather low, which results in a rather difficult gas extraction condition in this mining district. The permeability in the hard sublayer is approximately 0.025 mD, while that in the soft one is just approximately 0.002 mD. The permeability in the soft sublayer is approximately one order of magnitude less than that in the hard one.

2.2 | Technology synopsis

To improve the gas extraction efficiency in the Yangquan No.5 coalmine, the hydraulic flushing technology (Figure 2) has been adopted since 2017. The main principle of this technology is to wash out some coal mass to form a series of hydraulic cavities in the coal seam by adopting the high-pressure water jet. The flushing cavities could be provided enough space for the deformation of the coal mass; as a result, stress unloading and permeability increasing could be achieved in the surrounding coal. In the Yangquan No.5 coalmine, the hard coal is of higher mechanical strength; as a result, only the soft coal could be flushed out. Therefore, the flushing cavities present the rectangular shape.

3 | GAS EXTRACTION MODEL

3.1 | Mechanical strength and failure behavior of the coal mass

During the hydraulic flushing process, the stress state in the surrounding coal mass changes significantly; as a result, adopting an appropriate constitutive model to describe its mechanical behavior is essential. According to the previous research, coal mass is a typical strain-softening material and its failure is a progressive process; therefore, the strain-softening model is selected in this work. In the strain-softening
model, the entire stress-strain curve is usually divided into three stages: elastic stage, strain-softening stage, and residual stage. Meanwhile, these stages could be described by the strain-softening parameter $\gamma_p$. In the elastic stage, plastic failure does not occur; as a result, this stage could be described as follows: $\gamma^p = 0$. Assuming that the transition value of the strain-softening parameter at the start of the residual stage is $\gamma^{p*}$, the strain-softening stage and the residual stage could be described by $0 < \gamma^p < \gamma^{p*}$ and $\gamma^p \geq \gamma^{p*}$, respectively.

The increment softening parameter ($\gamma^p$) is commonly expressed as follows:

$$
\gamma^p = \frac{\Delta \gamma^p}{\Delta \tau} = \sqrt{\frac{2}{3} \left( 3 \epsilon^p_1 \epsilon^p_2 + \epsilon^p_2 \epsilon^p_3 + \epsilon^p_3 \epsilon^p_1 \right)}
$$

(1)

where $\epsilon^p_1$, $\epsilon^p_2$, and $\epsilon^p_3$ are the principal plastic strains, and $\tau$ is the time variable.

Moreover, it is generally considered that the cohesion decreases during the strain-softening process while the fraction remains unchanged. Assuming that the cohesion decreases linearly with the softening parameter in the strain-softening stage, the cohesion evolution of the strain-softening coal mass could be expressed as follows:

$$
c = \begin{cases} 
c_0 - (c_0 - c_r) \gamma^p / \gamma^{p*}, & \gamma^p < \gamma^{p*} \\
\gamma^{p*} & \gamma^p \geq \gamma^{p*} \end{cases}
$$

(2)

where $c$ represents the cohesion; $c_0$ represents initial cohesion, and $c_r$ represents residual cohesion.

Besides, the Mohr-Coulomb (MC) criterion is chosen for the failure criterion of the coal mass in this work.

### 3.2 | Permeability model

Permeability is an important parameter for the gas flow especially in the coal reservoir. During the hydraulic flushing process, the permeability evolution in the coal mass is closely related to its stress state. According to the permeability evolution of the coal mass in the entire stress-strain process, the permeability in the elastic stage is mainly affected by the volumetric stress. When the volumetric stress decreases, the initial cracks open; as a result, the permeability increases. On the contrary, the permeability would decrease. However, in the postpeak stage, the permeability evolution is much more complex. This is because a lot of new microfractures will generate during this process, which could result in a sharp increase in the coal permeability. Meanwhile, it is generally considered that the generation of the new cracks and the permeability increase mainly occur in the plastic softening stage; Wang and Park). In the plastic residual stage, the generation of new cracks is rather weak; as a result, the permeability almost remains the same. Therefore, An et al. and Tu et al. have reported a permeability model that could describe the permeability evolution in the entire stress-strain process. According to their model, the permeability in the surrounding coal after hydraulic flushing could be expressed as follows:

$$
k_1 = \begin{cases} 
k_0 \exp (- C_f \Delta \Theta), & \gamma^p = 0 \\
k_0 (1 + \gamma^p / \gamma^{p*}) \xi \exp (- C_f \Delta \Theta), & 0 < \gamma^p < \gamma^{p*} \\
k_0 (1 + \xi) \exp (- C_f \Delta \Theta), & \gamma^p \geq \gamma^{p*} \end{cases}
$$

(3)

where $k_1$ is the permeability after hydraulic flushing, mD; $k_0$ is the initial permeability, mD; $C_f$ is the cleat volume compressibility, MPa$^{-1}$; $\Theta$ is the volumetric stress, MPa; and $\xi$ is the permeability jump coefficient.

### 3.3 | Gas diffusion equation

According to the previous research, coal mass is a typical dual-porosity media and more than 95% of the total gas stores in coal matrix. During the gas extraction process, gas contained in the coal matrix first diffuses into the fractures and then flows through the fracture system. Generally, the gas diffusion in the coal matrix is considered to be concentration-derived and follows Fick’s law. Therefore, the gas pressure change in the coal matrix could be expressed as follows (derivation procedure is discussed in “Appendix A”):

$$
am_{pm} \frac{\partial p_m}{\partial t} = \frac{100 V_m (1 + 0.31W) \rho_m + p_l^2 \rho_m - p_f}{\varepsilon RT \rho_c (100 - A - W) V_m \rho_l + 100 \varepsilon RT (1 + 0.31W) \rho_m + p_l^2 \rho_m} \frac{\partial p_m}{\partial \Theta} \Delta \Theta
$$

(4)

### 3.4 | Gas flow equation

According to the mass conservation law and considering per volume of coal in unit time, the variation of the amount of free gas in the fractures is equal to the difference between the amounts of gas that diffuses into fractures and that flows out of fractures. As a result, the gas mass conservation equation for the fracture is Ref. The gas diffusion equation in Equation 4, and the gas flow equation in Equation 5, the gas extraction model for the hydraulic flushing borehole is established. In this work, the gas extraction model is solved by using the COMSOL Multiphysics software. Specially, the mechanical analysis is conducted by using the solid mechanics module, and the gas flow analysis is implemented by the PDE module. After the mechanical...
analysis, the stress and strain data could be obtained, and thus, the permeability evolution could be calculated. Then, the calculated permeability data are substituted into the PDE module to analyze the gas extraction, as shown in Figure 3.

4 | GAS EXTRACTION ENHANCEMENT MECHANISM AND MAIN INFLUENCE FACTORS

4.1 | Geometric model and boundary condition

In this work, a two-dimensional geometrical model was built according to the plane-strain assumption for simplification, as shown in Figure 4. The length of the model was set as 40 m, and its thickness was set as 18.2 m. The coal seam was located at the center of the model. Its roof and floor are mudstones, and their thickness is 6.0 m. The flushing width was set as 1.6 m. As for the boundary and initial conditions, they were separately set for the solid deformation model and gas flow model. For the solid deformation model, the right and bottom sides were set as roller boundaries, while the top and left sides were set as the stress boundaries. The initial vertical stress was set as 9.41 MPa, and the lateral stress coefficient (λ) was set as 0.35. For the gas flow model, the external boundaries of the coal seam were no flow boundaries, while those of the flushing borehole were constant pressure boundaries with a value of 87 kPa. The gas extraction time was set as 300 days, and the initial gas pressure was 1 MPa. Meanwhile, the related parameter values used during the simulation process were listed in Appendix B.

According to the geological model and boundary conditions in Figure 4 and the parameter values in Appendix B, we first took a flushing width of 1.6 m as an example to illustrate the gas extraction enhancement mechanism of this new technology in this section. On this basis, the effects of the flushing width and geostress field on the gas extraction were also evaluated and discussed. Meanwhile, during the simulation process, 6 monitoring lines and one monitoring point were set: A1B1 at the top of the upper hard sublayer; A2B2 at the middle of the upper hard sublayer; A3B3 near the bottom of the upper hard sublayer; A4B4 at the top of the soft sublayer; A5B5 at the middle of the soft sublayer; A4A6 near the flushing boundary; and B6 (monitoring point) at the top of the soft sublayer. The coordinates of the related points were as follows: A1 (20 m, 12.2 m); B1 (40 m, 12.2 m); A2 (20 m, 10.7 m); B1 (40 m, 10.7 m); A3 (20 m, 9.7 m); B3 (40 m, 9.7 m); A4 (21 m, 9.2 m); B4 (40 m, 9.2 m); A5 (20 m, 9.1 m); B5 (40 m, 9.1 m); A6 (21 m, 9.0 m); and B6 (24 m, 9.2 m).

4.2 | Gas extraction enhancement mechanism

4.2.1 | Permeability evolution

Under a flushing width of 1.6 m, the stress redistribution, plastic failure, and permeability evolution in the surrounding coal mass after hydraulic flushing have been obtained, as shown in Figure 5.

Figure 5A shows the minimum principal stress cloud charts after hydraulic flushing, from which we can see that the minimum principal stress decreases in the surrounding coal mass, resulting in an X-shaped stress-unloading zone. Beyond the stress-unloading zone, the minimum principal stress increases, and thus, a cross-shaped concentration zone occurs. However, different to the minimum principal stress, the maximum principal stress decreases in the upper and lower sides, while that increases in the left and right sides (Figure 5B). Moreover, the evolution of the volumetric stress is also presented (Figure 5C) considering that the permeability of the coal mass is directly related to the volumetric stress (Equation 3). From Figure 5C, we can see that the volumetric stress almost exhibits the same evolution pattern as that of the maximum principal stress. In addition, a butterfly-shaped plastic zone is also formed due to the un-coordinate evolution of the maximum principal stress and the minimum principal stress.
stress (Figure 5D). With the stress redistribution and the coal mass failure, the permeability in the hard sublayer improves significantly near the flushing borehole (Figure 5E,F). In the plastic zone, the permeability could increase by hundreds of times. However, different with the hard sublayer, the permeability in the soft sublayer decreases notably due to the stress concentration.

The same pattern could also be observed in the permeability monitoring results in Figure 6. During the simulation process, the monitoring lines A1B1, A2B2, and A3B3 were adopted to monitor the permeability evolution in the hard sublayer, while A5B5 was adopted to monitor that in the soft sublayer. Figure 6A-C shows the permeability monitoring results in the hard sublayer. From these figures, we can also see that the nearer to the flushing borehole, the greater the permeability-increasing magnitude in the hard sublayer, while the permeability-increasing zone is much smaller. Meanwhile, the stress concentration beyond the permeability-increasing zone is also increasingly serious. At the top of the hard sublayer (monitoring line A1B1), the maximum permeability ratio in the permeability-increasing zone is just 1.22 (Figure 6A); that is, the maximum permeability-increasing magnitude is 22%. However, the radius of the permeability-increasing zone reaches up to 2.7 m. Besides, the maximum volumetric stress in the permeability-decreasing zone is just 17.01 MPa, which is slightly greater than its initial value (16.73 MPa). As a result, the maximum permeability-decreasing magnitude is just 4% (the permeability ratio is 0.96). At the middle of the hard sublayer (monitoring line A2B2), the maximum permeability-increasing magnitude reaches up to 97% in the permeability-increasing zone, while its radius decreases to 1.64 m (Figure 6B). At the same time, the maximum permeability-decreasing magnitude increases to 12%. Near the bottom of the up hard sublayer (monitoring line A3B3), the equivalent plastic shear strain is greater than 0 near the flushing borehole (Figure 6C); that is, plastic failure occurs there. In the plastic zone, the maximum permeability increases by 88 times. In addition, the radius of the permeability-increasing zone decreases to 1.2 m, and the maximum permeability-decreasing magnitude increases up to 54%.

Figure 6D shows the permeability monitoring results in the soft sublayer, from which we can see that plastic failure and stress redistribution also occur in the soft sublayer after hydraulic flushing. At the flushing boundary, the permeability increases by 107 times. However, the width of the permeability-increasing zone decreases to 1.2 m. Meanwhile, the soft coal suffers great stress concentration. The maximum volumetric stress reaches up to 60 MPa (3.59 times its initial value), and the maximum permeability-decreasing magnitude reaches up to 75%.

The permeability monitoring results show that the permeability increases significantly in the upper and lower hard sublayer, while that decreases notably in the soft one due to the stress concentration. Meanwhile, due to the fact that the initial permeability in the soft sublayer is approximately one order of magnitude less than that in the hard one, the permeability difference between these two sublayers would be rather great after hydraulic flushing.
4.2.2 Gas migration pattern in the soft sublayer

On basis of the permeability evolution results, the gas extraction simulation was also conducted. After 300 days’ gas extraction, the GC cloud charts are shown in Figure 7. From Figure 7, we can see that the GC decreases significantly both in the hard sublayer and in the soft one when the gas extraction starts; that is, the permeability decrease in the soft sublayer seems to have a little effect on its gas extraction. Therefore, the gas migration pattern in the soft sublayer during the gas extraction process is evaluated in this section.

According to Darcy’s law, the gas flow in the coal seam is driven by the gas pressure gradient in the fractures. Considering that the permeability in the soft sublayer is much lower than that in the hard one after hydraulic flushing, the fracture gas pressure (FGP) tends to decrease more significantly in the hard sublayer under the same gas extraction time; that is, a vertical FGP gradient may form around their interfaces. Therefore, the evolution of the vertical FGP gradient during the gas extraction process is also presented, as shown in Figure 8A. From Figure 8A, we can see that a negative vertical FGP gradient forms at the upper side of the soft sublayer. According to Darcy’s law, the gas there would flow into the upper hard sublayer. On the contrary, the vertical FGP gradient at the lower side of the soft sublayer is positive; that is, the gas would flow into the lower hard sublayer. The evolution of the vertical FGP gradient is in good accordance...
ZHANG et al. with our guess. Therefore, the gas in the soft sublayer has two flow manners during its gas extraction process (Figure 8B): (a) directly flows into the borehole along the soft sublayer under the gas extraction pressure (bedding gas flow), and (b) firstly flows into the hard sublayer along the vertical direction under the vertical FGP gradient and then flows into the borehole (interlayer gas flow).

To evaluate the main gas flow manner in the soft sublayer, its interlayer gas flow rate and the bedding gas flow rate were also monitored by adopting the monitoring line A4B4 and A4A6 (Figure 4), respectively. These two monitoring lines aimed to separate the permeability-increasing zone in the soft sublayer because the gas in the hard sublayer may flow into this zone during the gas extraction process. Therefore, the coordinates of the related points were set as follows: A4 (21 m, 9.2 m), B4 (40 m, 9.2 m), and A6 (21 m, 9.0 m). Meanwhile, the monitoring results by A4B4 and A4A6 have been multiplied by 4 and 2, respectively, considering the symmetry of the geometric model. The monitoring results are shown in Figure 9A, and their ratio (interlayer gas flow rate/bedding gas flow rate) is presented in Figure 9B. From Figure 9, we can see that the interlayer gas flow rate is significantly greater than that of the bedding gas flow, indicating that it is the main gas flow manner in the soft sublayer. This is because the low permeability in the soft sublayer seriously limits its bedding gas flow. However, during the interlayer gas flow process, the low permeability has a little effect on the gas flow due to the fact that the thickness of the soft sublayer is rather small.

### 4.2.3 Gas extraction enhancement mechanism

According to Section 4.2.1, the permeability evolution in the hard sublayer is different with that in the soft one during the hydraulic flushing process. Meanwhile, according to the gas flow characteristic in the soft sublayer, interlayer gas flow is its main flow manner during the gas extraction process. Therefore, their permeability sensitive is analyzed under this special gas extraction condition to better understand the gas extraction enhancement of this new technology in this section.

In this section, 5 simulation cases were set (Table 1). The gas simulation in section 4.2.2 was set as Case 1, which could be considered as a standard Case. In Case 2, the values of cleat volume compressibility and the permeability jump coefficient in the hard sublayer were set as 0; that is, its permeability did not change during the hydraulic flushing process. In Case 3, the initial permeability in the hard sublayer was set as 0.05 mD (2 times that in Case 1), while the other parameters were the same as those in Case 1. By comparing the gas extraction results among Cases 1 to 3, the effect of permeability in the hard sublayer on the gas extraction could be obtained. Moreover, Case 1, Case 4, and Case 5 were also adopted to analyze the permeability sensitive in the soft sublayer. In
Case 4, the values of cleat volume compressibility and the permeability jump coefficient in the soft sublayer were set as 0; that is, its permeability remained the same during the hydraulic flushing process. In Case 5, the initial permeability in the soft sublayer was set as 0.00002 mD, which decreases by two orders of magnitude when compared with that in Case 1.

During the simulation process, the monitoring point B6 (Figure 4) was adopted to monitor the evolution of the vertical FGP gradient under different cases. The monitoring results are shown in Figure 10. From Figure 10A, we can see that the vertical FGP gradient is the greatest in Case 3, while that is the least in Case 2. Therefore, under the same permeability in the soft sublayer, the vertical FGP gradient increases with the permeability in the hard one. From Figure 10B, we can see that the vertical FGP gradient is the greatest in Case 5, while that is the least in Case 4, suggesting that the vertical FGP gradient increases with the decrease in the permeability in the soft sublayer under the same permeability in the hard one. According to the vertical FGP gradient monitoring results, we can conclude that it increases with the permeability difference between different sublayers.

Meanwhile, the gas extraction data and the residual GCs in the soft sublayer were also monitored under different simulation cases by adopting the monitoring lines A4B4, A4A6, and A5B5, as shown in Figure 11. In Cases 1 to 3, the permeability values in the soft sublayer are the same. However, as shown in Figure 11A, their interlayer gas flow rates are rather different, indicating that the permeability in the hard sublayer has a great effect on the interlayer gas flow. Compared with Case 2, the interlayer gas flow rate in Case 1 is much greater. This is caused by the permeability increase in the hard sublayer during the hydraulic flushing process. With the increase in the coal permeability in the hard sublayer (Case 1), the vertical FGP gradient increases in the soft sublayer (Figure 10A). According to Darcy’s law, the increase in the vertical FGP gradient will promote the interlayer gas flow. Therefore, the interlayer gas flow rate in Case 1 is much greater than that in Case 2 (Figure 11A). Figure 11B shows the bedding gas flow
rates under different cases, from which we can see that the bedding gas flow rate in Case 1 is lower than that in Case 2. However, as shown in Figure 11A,B, the interlayer gas flow rate is significantly greater than the bedding gas flow rate. Therefore, the total gas flow rate in Case 1 is also greater than that of Case 2 (Figure 11C). Moreover, after 300 days’ gas extraction, the residual GCs in the soft sublayer under Case 1 are also much lower (Figure 11D).

Besides, compared with Case 1 and Case 2, the permeability in the hard sublayer under Case 3 is the greatest; as a result, its gas extraction effect is the best (Figure 11C,D). The gas extraction results in Cases 1 to 3 show that the permeability in the hard sublayer could also have a great effect on the gas extraction in the soft sublayer. As it increases, the vertical FGP gradient increases in the soft sublayer, which promotes its interlayer gas flow rate. As a result, the gas extraction effect improves.

In Case 1, Case 4, and Case 5, the permeability values in the hard sublayer are the same. From Figure 11A, we can see that the interlayer gas flow rate in Case 1 is also greater than that in Case 4. Compared with Case 4, the permeability in the soft sublayer decreases notably in Case 1 due to the stress concentration caused by hydraulic flushing. Therefore, the increase in the interlayer gas flow rate in the soft sublayer is caused by the increase in the vertical FGP gradient, as shown in Figure 10B. Meanwhile, as shown in Figure 11B, the bedding gas flow rate in Case 1 is obviously less than that in Case 4, indicating that the permeability decrease in the soft sublayer further limits its bedding gas flow. However, due to the increase in the interlayer gas flow rate, the decrease in the total gas flow rate in Case 1 is rather weak (Figure 11C), and its residual GC curve almost overlaps completely with that of Case 4 after 300 days’ gas extraction (Figure 11D). Besides, the same conclusion could also be found in Case 5. Even though the permeability in the soft sublayer decreases by two orders of magnitude in Case 5, its effect on gas extraction is also weak (Figure 11C,D). The simulation results in Case 1, Case 4, and Case 5 show that the decrease in the permeability in the soft sublayer limits its bedding gas flow. However, the vertical FGP gradient in the soft sublayer increases, which improves its interlayer gas flow rate. Therefore, the decrease in the total gas extraction rate is rather weak; that is, the permeability in the soft sublayer has a little effect on its gas extraction.

According to the above analysis, we can conclude that the gas extraction in the soft sublayer is mainly controlled by the permeability in the hard sublayer instead of that in the soft one under this special gas extraction condition in the Yangquan No.5 coalmine. During the hydraulic flushing process, the permeability increase in the hard sublayer could enhance the gas extraction both in the hard sublayer and in the soft one. On the contrary, the permeability decrease in the soft sublayer has little effect on its total gas flow rate, although the bedding gas flow rate shows an obvious decreasing trend. This is the gas extraction enhancement mechanism of this new technology.

4.3 Effect of flushing width on gas extraction

In this new technology, flushing width is the main parameter. Therefore, its effect on gas extraction is evaluated in this section. The field application results in the Yangquan No.5 coalmine show that the maximum flushing width could reach up to 1.6 m. Therefore, the following flushing widths are selected in this work: 0.6 m, 0.8 m, 1.0 m,
1.2 m, 1.4 m, 1.6 m, 1.8 m, and 2.0 m. Under these flushing widths, the permeability evolution ratio cloud charts are shown in Figure 12, from which we can see that the permeability-increasing effect improves significantly with the flushing width.

Moreover, the permeability evolution results are also monitored, as shown in Figure 13. Figure 13A shows the permeability evolution at the top of the hard-soft layer, from which we can see that the range of the permeability-increasing zone does not change much, while the maximum permeability ratio
increases from 1.02 to 1.26, with the flushing width increases from 0.6 m to 2.0 m. The permeability-increasing level improves significantly. Figure 13B illustrates the evolution of the maximum equivalent plastic shear strain, the area, and the maximum permeability ratio in the plastic zone of the hard sublayer. As shown in Figure 13B, the maximum equivalent plastic shear strain increases from 0.006 to 0.032 and the area of the plastic zone increases from 0.3 m² to 2.4 m², suggesting that the plastic failure is much more significant with the increase in the flushing width. Accordingly, the maximum permeability ratio increases from 81 to 329. The permeability monitoring results in the soft sublayer are shown in Figure 13C. From Figure 13C, we can see that the minimum permeability ratio in the soft sublayer decreases from 0.49 to 0.13; that is, the stress concentration is increasingly serious as the flushing width increases.

According to Section 4.2.3, the gas extraction in the soft sublayer is mainly controlled by the permeability in the hard one. Therefore, the gas extraction condition improves significantly as the flushing radius increases. This conclusion could be verified by the gas extraction results in Figure 14. Figure 14A shows the residual GC monitoring results at the middle of the soft sublayer after 300 days’ gas extraction. From Figure 14A, we can see that the GC decreases much more significantly under a greater flushing width. In the Yangquan No.5 coalmine, the GC of 8 m³/t is the criterion adopted to evaluate the effective influence zone of the borehole; that is, the effective influence zone is defined as the region where the GC is less than 8 m³/t. In this work, the width of the effective influence zone (WEIZ) in the soft sublayer is adopted to evaluate the gas extraction effect. Therefore, the WEIZs in the soft sublayer after 300 days’ gas extraction under different flushing widths are calculated according to the GC monitoring results in Figure 14A. The calculation results are shown in Figure 14B. From Figure 14B, we can see that the WEIZs in the soft coal sublayer at 300 days increases from 3.77 m to 5.51 m as the flushing width increases from 0.6 m to 2.0 m. Therefore, increasing the flushing width is an effective way to enhance the gas extraction.

**FIGURE 13** Permeability evolution monitoring results under different flushing widths: A. At the top of the hard sublayer; B. In the plastic zone of the hard sublayer; C. In the soft sublayer and D. Permeability decrease in the stress concentration zone.
4.4  Effect of geostress field on the gas extraction

According to the field determined geostress data in the Yangquan coalfield, the value of the maximum horizontal stress could be more than 2 times that of the vertical stress; as a result, the following λs are selected in this work: 0.25, 0.5, 0.75, 1.0, 1.25, 1.75, 2, 2.25, and 2.5.

Figure 15 shows the volumetric stress evolution under different λs, from which we can see that the shape and size of the stress-unloading zone are closely related to the horizontal stress. When λ \leq 0.5, the volumetric stress decreases significantly at the upper and lower sides of the borehole; that is, a vertical stress-loading zone forms. However, as λ increases, the vertical stress-unloading zone shows an obvious reduction trend. When λ is around 1.25, the stress-unloading effect is poor. After then, with the further increase of λ, a horizontal stress-unloading zone occurs gradually. Meanwhile, the greater the λ, the horizontal stress-unloading effect trends to be much better. Obviously, the horizontal stress-unloading zone is much more beneficial to the gas extraction.

Moreover, the shape and the area of the plastic zone also vary with λ (Figure 16). When λ < 0.5, the plastic zone presents a butterfly shape. With the increase of λ, the area of the plastic zone decreases. At a λ around 1, the plastic failure zone presents a quasi-circular shape and its size is approximately the smallest. After then, the plastic failure zone expands along the vertical direction with the further increase of λ.

According to the stress and plastic failure evolution results, the permeability ratio cloud charts are shown in Figure 17. From Figure 17, it can be seen that the vertical permeability-increasing effect weakens with the increase of λ at a low horizontal stress condition. Under a λ less than 0.5, the permeability-increasing effect is much stronger. However, under
the high horizontal stress condition, the greater the $\lambda$, the better the horizontal permeability-increasing effect. Therefore, this technology is more suitable for the extremely low horizontal stress condition ($\lambda < 0.5$) or the extremely high horizontal stress condition ($\lambda \geq 2$). This conclusion could also be verified by the gas extraction results in Figures 18 and 19. Meanwhile, when $\lambda$ is around 1, the gas extraction effect is the worst.

5 | **MODEL VALIDATION AND FIELD APPLICATION**

5.1 | **Crawler-type drilling and flushing integrated equipment**

To construct the hydraulic flushing borehole in the Yangquan No.5 coalmine, a novel crawler-type drilling and flushing integrated equipment have been developed. The equipment includes the following parts (Figure 20): (a) a crawler-type water tank (Type: BQWL200/31.5, rated flow: 200 L/min, rated pressure: 31.5 MPa, the maximum volume of the water tank: 1200 L), which is used to provide the high-pressure water for the equipment; (b) a drilling rig (Type: ZDY4500LXY, rated speed: 70–240 r/min, rated power: 55 KW, rated torque: 1100–4500 N m), which is used for drilling and flushing; (c) high-pressure water transport devices, including a high-pressure resistant sealing rotator (applicable rotary speed: 0–350 r/min, nominal pressure 35 MPa), a high-pressure water tube (pressure resistance: 60 MPa), and a high-pressure-resistant sealing drill pipe (working pressure: 0–35 MPa), which are used to transport the high-pressure water; and (d) a coal mass collection instrument, including a coal-water mixture collection instrument and a crawler-type vibrating screen, which is used to collect the discharged coal mass. During the hydraulic flushing process, the discharged coal-water mixture is collected and transported to the crawler-type vibrating screen, where the coal and gas could be separated. The separated coal mass would be transport to the ground. It should be noted that the crawler-type vibrating screen could not be adopted when the coal and gas abnormal ejection always occur during the hydraulic flushing process. In the Yangquan No.5 coalmine, the initial gas content is just approximately 10 m$^3$/t. The gas emission quantity is relatively low during the hydraulic flushing process; as a result, the crawler-type vibrating screen was adopted. However, when a large amount of coal with gas is ejected out, the local gas concentration will increase to upper limit, such as the explosion limit on occasion. For the sake of safety, the hydraulic flushing work will be forced to cease. Under this circumstance, the coal-water-gas...
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separation instrument reported by Zou et al. should be adopted to collect the discharged coal and gas during the hydraulic flushing process.

This equipment could move freely in the underground coalmine, which greatly reduces the construction cost and the labor intensity of the workers; therefore, it has been widely adopted in the Yangquan No.5 coalmine. By adopting this new equipment, the construction procedures for a single flushing borehole are as follows:

1. Drilling an ordinary in-seam borehole in the soft sublayer: open the drilling nozzle of the drilling and flushing integrated bit, and drill the in-seam borehole to the design length;
2. Hydraulic flushing: after the drilling of the in-seam borehole in the soft sublayer, drill pipe backs out rotationally at a constant speed. During this process, increase the water pressure to 15 MPa, and open the flushing nozzle of the drilling and flushing integrated bit. The high-pressure water jet breaks up the soft coal mass, which is discharged through the borehole along with the water.

5.2  |  Model verification

In this new technology, the borehole spacing (BS) should be designed according to the effective influence zone of the hydraulic flushing borehole. To optimize the borehole design in the Yangquon No.5 coalmine, the effective influence zone of the hydraulic flushing borehole was determined in 2017. Therefore, the field determined result is adopted in this work to verify our gas extraction model.

5.2.1  |  Field test scheme

The determination produces in the Yangquon No.5 coalmine are as follows: (a) constructing the hydraulic flushing borehole: the flushing width is 1.6 m, and the efficient flushing length is 70 m, as shown in Figure 21; (b) sealing the borehole: After the construction of the hydraulic flushing borehole, the borehole is sealed, and the sealing length is 10 m; (c) gas extraction for 300 days: After the sealing of the borehole, gas extraction starts, and the gas extraction pressure is 87 kPa; and (d) determining the residual GCs: After the gas extraction, the GC monitoring boreholes are drilled to determine the residual GCs at different distance to the hydraulic flushing borehole. Considering that the gas flow in the soft sublayer is rather different with that in the hard one, the residual GCs at the middle of the both sublayers were determined. Meanwhile, three GC measuring points are designed for each GC monitoring borehole to minimize the measurement error.

5.2.2  |  Verification results

In this section, the field determined gas extraction data and the residual GCs are adopted to verify our gas extraction model. The comparison of the field determined gas extraction data and the simulated one is shown in Figure 22A. It should be noted that the thickness of the geometrical model in Figure 4 is set as 1 m; that is, the length of the borehole is 1 m. However, the effective extraction length of the hydraulic flushing borehole in Figure 21 is 70 m. Therefore,
the simulated gas extraction data in Figure 22A have been multiplied by 70. From Figure 22A, it can be seen that the simulated gas extraction data matches well with the field data.

Moreover, after 300 days of gas extraction, the residual GC determination result at each measurement point in Figure 21 is shown in Appendix C. According to the determination results, the average residual GC at each
monitoring borehole has also been compared with the residual GC distribution curves at the middle of the hard sublayer and the soft sublayer obtained by using the simulation method (Figure 22B). From Figure 22B, we can also see that the simulation results are also in good accordance with the field data, suggesting that our model is scientifically sound and could be adopted to analyze the gas extraction of the hydraulic flushing borehole.

**FIGURE 22** Model verification results: A, Gas extraction data and B, Residual GC in the coal seam

**FIGURE 23** Sketch maps of the borehole arrangement: A, Sectional view in the 8206 working face; B, Plan view in the 8206 working face; C, Sectional view in the 8402 working face; and D, Plan view in the 8402 working face
TABLE 2  The hydraulic flushing parameters in the 4th gas extraction unit of the 8402 working face

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<tr>
<th>Borehole number</th>
<th>Flushing pressure (MPa)</th>
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<th>Flushing length (m)</th>
<th>Mass of discharged coal (t)</th>
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<td>15</td>
<td>26</td>
<td>104</td>
<td>43.3</td>
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<td>2#</td>
<td>15</td>
<td>16</td>
<td>95</td>
<td>40.0</td>
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<tr>
<td>3#</td>
<td>15</td>
<td>17</td>
<td>98</td>
<td>40.5</td>
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<tr>
<td>4#</td>
<td>15</td>
<td>14</td>
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<td>15</td>
<td>18</td>
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<td>15</td>
<td>18</td>
<td>96</td>
<td>41.4</td>
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</tbody>
</table>

5.3  | Field application

5.3.1  | Borehole arrangement

In the past, the ordinary in-seam borehole gas extraction technology was adopted in the fourth mining district of the Yangquan No.5 coalmine. Taking the 8206 working face as an example, two rows of boreholes with a radius of 0.045 m were arranged in the hard sublayer during its gas extraction process (Figure 23A,B). The BS is only 3 m. However, due to the low permeability of the coal seam, the gas extraction efficiency is rather low and the gas extraction takes almost 540 days.

FIGURE 24  Comparison of the gas extraction effect: A, Gas extraction data; B, Gas desorption index of drilling cuttings; C, Quantity of drilling cuttings; and D, CH₄ concentration in the return air
The 8402 working face with an average buried depth of 480 m is also located at the fourth mining district. To enhance its gas extraction and thus decrease the gas extraction time to less than 300 days, the hydraulic flushing technology was adopted in 2017 (Figure 23C,D). The flushing width is 1.6 m. According to the gas extraction simulation results in Section 4.3, the WEIZ in the soft sublayer after 300 days’ gas extraction is approximately 10.48 m. Therefore, the BS should be set as 10.48 m. However, the BS is currently set as 9 m. Given this, the BS of the hydraulic flushing borehole could be further increased in the future.

5.3.2 | Comparison of the gas extraction effect

In China, a working face is usually divided into several gas extraction units, and the gas extraction data for all the boreholes in each unit are monitored. The 4th gas extraction unit in the 8402 working face and the 6th gas extraction unit in the 8206 working face are of the same geological condition, gas condition, and also the same area; as a result, the gas extraction data of these two units are selected to compare the gas extraction effect. In the 6th gas extraction unit of the 8206 working face, the BS is set as 3 m and 30 ordinary in-seam boreholes are drilled. However, in the 4th gas extraction unit at the 8402 working face, the BS increases up to 9 m, and only 10 hydraulic flushing boreholes are constructed. The hydraulic flushing parameters in the 4th gas extraction unit are shown in Table 2.

Although the borehole number decreases by 66.7% after adopting this new technology, the gas extraction efficiency increases significantly. Over the same gas extraction time (300 days), the comparison of the gas extraction data is shown in Figure 24A. From Figure 24A, we can see that gas extraction flow increases from approximately 3 m³/min (on average) to approximately 4 m³/min (on average), and the gas extraction concentration increases from approximately 10% (on average) to approximately 30% (on average) after adopting this new technology. Meanwhile, the 8402 working face has been mined for approximately 360 m until now. During this process, the gas adsorption index of drilling cuttings \((K_1)\), the quantity of drilling cuttings \((S)\), and the \(\text{CH}_4\) concentration in the return air were systematically determined, as shown in Figure 24B-D. In this work, the determination results are also adopted to compare the gas extraction effect. From Figure 24B,C, we can see that the gas desorption index of drilling cuttings and the quantity of drilling cuttings often exceed their critical values during the mining process of the 8206 working face. However, in the 8402 working face, these parameters decrease significantly, indicating that a much better gas extraction effect. Meanwhile, the \(\text{CH}_4\) concentration in the return air also decreases significantly (Figure 24D). The field application results show that the gas extraction

condition in the Yangquan No.5 coalmine improves significantly after adopting this new technology.

6 | CONCLUSIONS

In this work, we proposed a new gas extraction method for coal seams with soft sublayers. By adopting the engineering and geological background in the Yangquan No.5 coalmine, we analyzed the gas extraction enhancement mechanism and the main influence factors of this new method. Meanwhile, the gas extraction effect of this new method has been systematically investigated. The main conclusions are as follows:

1. After hydraulic flushing in the soft sublayer, stress-unloading and plastic failure could be achieved in the overlying and underlying hard coal masses, which significantly improves their gas extraction condition. Moreover, stress concentration occurs in the soft sublayer; thus, its permeability decreases notably. Under this special gas extraction condition, interlayer gas flow is the main gas flow manner in the soft sublayer, and its flow rate is mainly controlled by the permeability in the hard sublayer. Therefore, the permeability decrease in the soft sublayer has little influence on its gas extraction. On the contrary, the permeability increase in the hard sublayer could significantly enhance its gas extraction.

2. The gas extraction effect of the hydraulic flushing borehole is mainly affected by the flushing width and the geostress condition. With the increase in flushing width, the stress-unloading effect and permeability-increasing effect improve in the hard sublayer, which results in a better gas extraction effect. Meanwhile, under an extremely low horizontal stress condition \((\lambda < 0.5)\) or an extremely high horizontal stress condition \((\lambda \geq 2)\), the gas extraction effect is much better. Therefore, this method is more suitable for the extremely low horizontal stress condition \((\lambda < 0.5)\) or extremely high horizontal stress condition \((\lambda \geq 2)\).

3. After adopting this new gas extraction method, the borehole number in the Yangquan No.5 coalmine decreases by 66.7%. However, the average gas extraction flow increases by 1.33 times and the average gas flow concentration increases by 3 times. Meanwhile, the gas adsorption index of drilling cuttings, the quantity of drilling cuttings, and the \(\text{CH}_4\) concentration in the return air also decrease significantly. Therefore, the gas extraction condition in the Yangquan No.5 coalmine improves significantly.

ACKNOWLEDGEMENTS

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**APPENDIX A**

Gas release from coal matrix is derived by the gas concentration difference, and the gas exchange rate can be represented as Ref. 47,48

\[
Q_m = \frac{1}{\tau} (c_m - c_f)
\]  

where \( Q_m \) is the gas exchange rate per volume of the matrix blocks, \( \text{kg/(m}^3\text{s)} \); \( c_m \) is the gas concentration in the matrix blocks, \( \text{kg/m}^3 \); \( c_f \) is the gas concentration in the fractures, \( \text{kg/m}^3 \); and \( \tau' \) is the “sorption time,” and it is numerically equivalent to the time during which 63.2% of the coal gas content is desorbed, s. Moreover, it has a reciprocal relationship with the diffusion coefficient and the shape factor\(^{37,47,49,50} \):

\[
\tau' = \frac{1}{D \sigma_c}
\]

where \( D \) is the gas diffusion coefficient, \( \text{m}^2/\text{s} \); \( \sigma_c \) is the shape factor of the coal matrix, \( \text{m}^{-2} \). The shorter the sorption time, the easier the gas diffusion.

Assuming that methane behaves as an ideal gas, the gas concentrations in the matrix blocks and fractures could be calculated using the ideal gas law\(^{37,49} \):

\[
c_m = \frac{M}{RT} p_m
\]

\[
c_f = \frac{M}{RT} p_f
\]

where \( M \) is the molar mass of methane, \( \text{g/mol} \); \( R \) is the gas constant, \( J/(\text{mol K}) \); and \( T \) is the gas temperature, \( \text{K} \).
Based on the gas mass conservation law in the coal matrix,37,49 we have

\[
\frac{\partial m}{\partial t} = -Q_m
\]  

(A5)

where \( t \) is gas extraction time, s; \( m \) is the gas content in the coal matrix, \( m^3/t \), which can be calculated using the Langmuir equation and the ideal gas law5,6,51,52:

\[
m = \frac{V_L p_m}{p_m + p_L} \frac{M}{V_M} \frac{100 - A - W}{100} + \phi_m \frac{M}{RT} p_m
\]  

(A6)

where \( V_L \) is the maximum adsorption capacity of the coal, \( m^3/kg \); \( p_L \) is the Langmuir pressure constant, MPa; \( V_M \) is the molar volume of methane under standard conditions, L/mol; \( p_m \) is the coal density, kg/m\(^3\); \( A \) is the ash content of the coal mass, \%; \( W \) is the moisture content, \%; and \( \phi_m \) is the coal matrix porosity, \%.

By substituting Equation A1, Equation A3, Equation A4, and Equation A6 into Equation A5, we can obtain the governing equation for the change in gas pressure in the coal matrix:

\[
\frac{\partial p_m}{\partial t} = -\frac{100V_M(1 + 0.31W)(p_m + p_L)^2(p_m - p_f)}{\tau' RT p_r (100 - A - W)V_L p_L + 100\tau' V_M(1 + 0.31W)(p_m + p_L)^2\phi_m}
\]  

(A7)

Equation A7 is the same as Equation 4.

**APPENDIX B**

<table>
<thead>
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<th>TABLE B1 Parameter values</th>
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<td>Elastic modulus of mudstone ((E_r, \text{ GPa}))</td>
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<td>Poisson's ratio of mudstone ((\nu_r))</td>
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<td>Cohesion of mudstone ((c_r, \text{ MPa}))</td>
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<td>Friction angle of mudstone ((\phi_r, ^\circ))</td>
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<td>Density of mudstone ((\rho_r, \text{ t/m}^3))</td>
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<td>Elastic modulus of soft coal mass ((E_{c_1}, \text{ GPa}))</td>
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<td>Critical strain-softening parameter of soft coal mass ((\gamma^{*}_{c_1}))</td>
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<td>Maximum adsorption capacity of soft coal mass ((V_{L_1}, \text{ m}^3/\text{t}))</td>
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(Continues)
### APPENDIX C

#### TABLE B1 (Continued)

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#### TABLE C1  The residual GC determination results

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