An improved method for high-efficiency coal mine methane drainage: Theoretical analysis and field verification

Qingquan Liu¹,² | Hongxing Zhou¹,² | Yuanping Cheng²,³ | Longyong Shu⁴ | Barkat Ullah²

¹Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou, China
²School of Safety Engineering, China University of Mining and Technology, Xuzhou, China
³National Engineering Research Center for Coal and Gas Control, China University of Mining and Technology, Xuzhou, China
⁴Mine Safety Technology Branch, China Coal Research Institute, Beijing, China

Abstract

Degassing a coal seam with in-seam boreholes is an important method for mitigating the gas hazards in the underground coal mine. However, the low strength of the outburst-proven coal limits the borehole sealing performance and borehole space maintaining, and thus influences the drainage performance of in-seam boreholes. This study was conducted to seek a method to improve the sealing performance and borehole space maintaining for high-efficiency CMM drainage. A visco-elastic plastic model involving the plastic softening and dilatancy features for soft coal was proposed, and the deformation, shrinkage, and fracture characteristics of the coal surrounded a borehole and a roadway were analyzed. An enormous amount of connective fractures generated in the failure zone and the plastic zone, and the plastic zone develops timely for the creep behavior of coal, which aggravates the difficulties of borehole sealing. A comprehensive approach including the theoretical method and the technical method was developed to determine the proper sealing depth which can significantly influence the sealing performance. The sieve tubes made of high-density polyethylene has been used to maintain the borehole space during the scheduled pre-drainage period. A series of field tests were conducted in an outburst-proven coal seam to verify the feasibility of the comprehensive approach and the borehole space maintaining method. Field tests showed that the comprehensive approach to determine the proper sealing depth and the installing of sieve tubes to protect the borehole space can provide favorable conditions for maximum CMM pre-drainage from outburst-prone coal and maximum utilization of the in-seam boreholes.

KEYWORDS

borehole sealing, coal mine methane, field verification, gas drainage, in-seam borehole

1 INTRODUCTION

The coal and gas outburst is a natural threat, an accompanying underground coal miners’ daily work. The hazard of this phenomenon is currently increasing sine deeper and deeper coal-beds are being prepared for extraction.¹ CMM pre-drainage is generally believed to be one of the most effective methods to manage and eliminate outburst dangers.²,³ Cross-measure boreholes and in-seams boreholes are widely used for CMM pre-drainage in China.⁴,⁵ Cross-measure boreholes are drilled from roadways in the roof strata or the floor strata, and in-seam boreholes are directly drilled in the coal
seam. It is generally accepted that the in-seam boreholes are with higher cost performance than cross-measure boreholes in CMM pre-drainage. According to the national law on coal mine safety, all of the underground coal mines with outburst hazard drilled a significant amount of in-seam boreholes for CMM pre-drainage in the past 10 years. For example, underground coal mines with outburst hazard from Huai’bei coalfield in China drilled approximately 12 000 in-seam boreholes (which are totally 840 km long) a year.

As in-seam boreholes are directly drilled in the coal seams, continuous high efficiency in CMM pre-drainage is expected. However, the common phenomenon in CMM pre-drainage with in-seam boreholes is sometimes disappointing. According to statistics, the methane concentration of approximately 80% of in-seam boreholes varies from 6% to 20% in China, and the gas mass flow can only maintain at a relatively high level at the initial period of pre-drainage (ie, 10-30 days), and then it may sharply decrease, and almost no methane can be extracted after 2 or 3 months. The fairly low gas mass flow and methane concentration present challenges to the feasibility, cost, and performance of CMM drainage in outburst-prone coal seams in China.

Many efforts, including protective seam mining technique, hydraulic flushing hole enlargement technique, hydraulic fracturing technique, etc. have been proposed to improve the efficiency of CMM drainage in outburst-prone coal seams. These efforts focused on enhancing coal permeability to improve the efficiency of CMM pre-drainage and reduce the number of boreholes.

Besides the coal permeability, CMM drainage efficiency is also closely related to the borehole sealing performance and flowing space. Zhou et al. presented a new second borehole sealing method to improve the sealing performance of the CMM drainage borehole. Zhai et al. performed research on a new composite sealing material of CMM drainage boreholes and tested its sealing performance. Fan et al. studied a new sealing device to improve the sealing performance of the CMM drainage borehole. Wang and Wu reviewed and analyzed the major sealing method of CMM drainage boreholes in China. It can be found that the sealing method, sealing material, sealing device, etc. have been studied by the researchers.

However, it is commonly accepted that the outburst-prone coal seams are characterized by low strength. The excavation of underground openings (including roadways and boreholes) has a significant effect on the in-situ stress distribution of the surrounding coal. A wide zone of coal surrounding the roadway becomes broken after excavation, thus a large number of fractures may appear around the borehole due to the disturbance superposition of multiple excavations. These fractures expand and connect over time, and finally influence the sealing performance. Furthermore, as the borehole acts as the methane flow channel, the failure of a borehole can significantly influence the drainage efficiency. Thus, the relationships between the underground excavations failure, sealing performance, and drainage efficiency need further study.

In this study, the failure mode of in-seam CMM drainage boreholes and the fracture characteristics of the coal surrounding a roadway were first analyzed using a visco-elastic plastic model while considering the plastic softening and dilatancy. The proper sealing depth of an in-seam borehole was studied based on the theoretical findings. Then some improvements in borehole space maintenance and borehole sealing were proposed to enhance the CMM pre-drainage performance. Finally, the research findings were implemented and verified in the field.

2 | THE MECHANICAL STATUS AND FAILURE MODE OF UNDERGROUND OPENINGS

2.1 Mechanical status around underground openings

Formations at depth are under a state of compressive in-situ stress. When an underground opening is excavated, the rock surrounding it must bear the load that was previously borne by the removed rock mass. In the following, the in-seam borehole which is a typical underground opening will be discussed as an example.

When a borehole is drilled, it can produce an increase in the tangential stress and a decrease in the radial stress in the surrounding rock (see Figure 1). Particularly, if the rock is not strong enough, the borehole may be easily destroyed by the redistributed in-situ stress. As coal is a typical soft rock with low strength, the redistributed in-situ stress can lead to the debonding of soft coal mass, resulting in a damaged zone surrounds the borehole.

FIGURE 1 Drilling-induced stresses around a borehole modified after
The coal in the damaged zone has lost most of its load capacity and lots of new fractures were generated during the failure process, resulting in the borehole failure. The borehole failure modes can be grouped into the following two classes: one is the borehole collapse induced by coal failed in a brittle manner, and the other one is the borehole shrinkage and finally compaction due to the creep behavior of the soft coal.22

### 2.2 Failure mode of the in-seam borehole

#### 2.2.1 In-seam borehole collapse

The damaged zone surrounded a borehole can be divided into a failure zone and a plastic zone. The failure zone was violently destroyed by the tangential stress concentration, and enormous fractures generated in the failure zone. These new fractures, combining with the primary fractures, created a densely meshed fracture system in the failure zone. Meanwhile, the radial stress relief in the failure zone can induce the extension, dilation, and connection of the fractures. As a result, the coal in the failure zone formed a macroscopic, extensive, and intersected fracture system. The fracture system can cut the coal into small blocks, which may easily spall by the gravity, resulting in the borehole collapse.

Generally, borehole collapse may not happen during or immediately after borehole drilling, that is, a borehole can maintain for a certain time. According to the Mohr-Coulomb criterion,23 the failure of coal in laboratory tests generally occurs along a weakness plane due to the in-situ stress redistribution. However, in the field, coal is in a three-dimensional contact state, and the weak plane cannot entirely separate from the coal mass. As a result, the coal in the damaged zone can’t immediately separate from coal mass. Particularly, when drilling the underground in-seam boreholes, the periodic impact loads induced by the drilling rod and drilling bit continue to disturb the borehole wall which now is the stress concentration-induced zone. As a result, strain softening of the coal mass in the post-peak state develops faster until the coal mass completely loses its load capacity, thus leading to a borehole collapse.24 The volume of coal powder extracted from a borehole is generally greater than the borehole volume itself. According to the statistical data of Huaibei Mining Group (China), the volume of coal powder extracted from a 113 mm diameter borehole is 2 or 3.5 times greater than the borehole volume itself.

The range of the failure zone is closely related to the mechanical parameters of the coal and the geological environments. Generally, the larger range of the failure zone, the greater the possibility of borehole collapse. Comparing with the hard coal, soft coal is usually with low strength, thus borehole drilling can lead to a larger range of damaged coal around boreholes.

#### 2.2.2 In-seam borehole shrinkage and compaction

The borehole stability is also significantly influenced by the creep behavior of soft coal. On the one hand, the creep deformation can promote the extension, connection, and expansion of the fractures in the damaged zone surrounding the borehole. On the other hand, the surrounding coal will progressively occupy the borehole space until filling the whole borehole space due to the coal creep deformation. Thus, the creep behavior of soft coal must be taken into account when analyzing the borehole shrinkage and compaction.

A visco-elastic plastic model considering the strain softening and dilatancy can be used to describe the borehole shrinkage and compaction in the soft coal. This model can describe the elastic deformation, plastic deformation, and creep deformation of soft coal. As shown in Figure 2, the initial in-situ stress in a coal seam is defined as $P_0$ (under hydrostatic pressure conditions), and the initial borehole radius is $a$. Due to the borehole drilling-induced stress concentration, there exists the failure zone, the plastic zone, and the visco-elastic zone around the borehole.

According to the visco-elastic plastic model, the visco-elastic zone can be described by Poynting-Thomson visco-elastic model, and the plastic zone and the failure zone can be described by plastic flow model.25,26 Thus, the displacement...
of the borehole wall $u_0$ can be calculated by the following equation\textsuperscript{27,28}:

$$u_0 = 2aA(t)\left\{\frac{1}{1+2m} + \frac{1}{1+n} \left[\frac{R_b}{a} \right]^{1+n} - 1\right\} \left[1 + \frac{m+1-\sigma_c}{2mGc} + \frac{m-1}{2(1+m)}\right],$$

where $R_b$ is the radius of the failure zone; $R_p$ is the radius of the plastic zone. The coal remains in the state of visco-elastic equilibrium beyond the plastic zone. $m$ is the dilation coefficient of the coal in the plastic zone; $n$ is the dilation coefficient of the coal in the failure zone; $M_c$ is the strain softening modulus of coal in the plastic zone; $\sigma_c$ is the uniaxial compressive strength of the coal; $\sigma_c^*$ is the residual strength of the coal; $A(t)$ is the function of time, which can be calculated by\textsuperscript{27,28}

$$A(t) = \frac{p0(K_p-1)+\sigma_c}{2(K_p+1)} \left\{\frac{1}{G_c} \left[1 - e^{-(t/\eta_{tec})}\right] + \frac{1}{G_a} e^{-(t/\eta_{tec})}\right\},$$

where, $G_0$ and $G_\infty$ are the initial and the long-term shear modulus of soft coal, respectively; $t$ is time and $\eta_{tec}$ is the rheological time of coal; $\rho_0$ is the initial in-situ stress; $K_p$ is related to the angle of internal friction $\phi$, and where $K_p = (1 + \sin \phi)/(1 - \sin \phi)$. The radius of failure zone $R_b$ is given by\textsuperscript{27,28}

$$R_b = a \left\{\frac{B_0 p0 + \frac{\sigma_c}{K_p} + \frac{M_c}{K_p-1} \left[\frac{2A(t)M_c + m + 1 - \sigma_c^*}{(m+1)K_p-1}\right]}{2K_p-1}\right\}^{1/(K_p-1)},$$

where $B_0$ is a function of time and can be written as\textsuperscript{27,28}

$$B_0 = \frac{2}{K_p+1} \left[\frac{2A(t)M_c}{2A(t)M_c + (m+1)\sigma_c^*}\right]^{(1/(K_p-1))}.$$

The residual radius $a'$ of an in-seam borehole in the shrink process is given by

$$a' = a - u_0.$$
also extended and generated due to the effects of the compressive loading and unloading on the coal, but the connectivity is weaker than that of the fractures in the failure zone. The coal permeability in the plastic zone is less than that in the failure zone, but it is still greater than the initial permeability.

In the visco-elastic zone, the tangential stress is also greater than the initial stress, and the coal is in the elastic state; the fractures mainly closed due to the effect of compressive loading on the coal. Therefore, the connectivity of the fractures is weaker than that of the initial fracture state, and the coal permeability is smaller than the initial permeability. The excavation of the roadway can hardly affect the uninfluenced zone; therefore, the in-situ stress conditions and permeability are almost equal to their initial state.

The proper sealing of the fractures is the foundation to achieve a high sealing performance of cross-measure CMM drainage boreholes. The schematic diagram of an in-seam borehole sealing is shown in Figure 4. When sealing an in-seam borehole, polyurethane is first fixed at both ends of the sealing part, and then, the main sealing material which is commonly expanding cement paste is injected into the interior space between the two polyurethane ends with a certain sealing pressure. The cement paste is expected to inject into the fractures and avoid the outside air leak in the interior space of the borehole. The sealing length represents the length of the sealing material, and the sealing depth represents the length from the end of the sealing material to the wall of the roadway. The sealing length is equal to or less than the sealing depth.

In-seam boreholes are drilled in the coal seam through the failure zone, the plastic zone and the visco-elastic zone around the roadway. As discussed above, an enormous amount of connective fractures generated in the failure zone and the plastic zone, and the plastic zone develops timely for the creep behavior of coal, which aggravates the difficulties of borehole sealing. The visco-elastic zone around the roadway is with low permeability, which acts as the natural barrier of air leakage. It is difficult for the outside air to leak into the borehole through the visco-elastic zone. Therefore, it can be deduced that the sealing length of an in-seam CMM drainage borehole should be at least equal to or greater than the radius of the plastic zone.

It is generally accepted that increases the sealing depth will be beneficial to decrease the air leakage into the drainage borehole. However, the sealing depth cannot be increased limitlessly due to the engineering cost, sealing technology, and especially the mining safety. As the sealing part of a borehole do not have the capacity to drainage methane, the reduction of methane exists within the sealing depth depends on a long-term self-emission.

After excavation of a roadway, the methane existed in the surrounding coal would gradually flow into the roadway due to the pressure difference, resulting in a methane self-emission zone around the roadway. In the methane self-emission zone, the energy (including gas potential energy and in-situ stress-energy) of triggering or developing an outburst has been greatly released, and the outburst hazards have been significantly weakened. It is generally accepted that the methane in this zone doesn’t need to be extracted before coal mining. Thus, the maximum sealing depth should be shorter than or equal to the radius of the methane self-emission zone around the roadway.

3.2 | Comprehensive approach to determine the proper sealing depth

3.2.1 | Theoretical method

As discussed above, the sealing depth of in-seam boreholes should be neither too short nor too long. On the one hand, the proper sealing depth should be beyond the plastic zone to avoid the air leakage through the fractures in the surrounding coal. On the other hand, the proper sealing depth should be within the methane self-emission zone to avoid a potential safety hazard. Thus, in the nonoverlapping zone of these two
zones, the increase of sealing depth will be beneficial to the CMM drainage efficiency.

The radius of the plastic zone is one of the most important factors to determine the proper sealing depth. The mechanical behavior of the roadway excavation is similar to the borehole drilling. The difference between the two typical underground openings is that there are supports on the opening wall of the roadway. Thus, the visco-elastic plastic model of soft coal should be modified to consider the influence of supports on the mechanical behavior, and the radius of the plastic zone of the roadway is given by\(^{32}\)

\[
R_b = a \left\{ b_0 \left[ \frac{1}{K_p - 1} + \frac{(K_p + 1)(A(t)M_c)}{(K_p - 1)(K_p + A_p) - \frac{2A(t)M_c + (m + 1)(\sigma_e - \sigma_e^*)}{2A(t)M_c}} \right] \right\}^{1/(K_p - 1)},
\]  

(6)

Where, \(p_1\) is the support resistance of the roadway, \(a\) is the radius of the roadway.

When considering the creep behavior of soft coal, the radius of the plastic zone around the roadway can be calculated by\(^{32}\)

\[
R_p = R_b \left[ \frac{2A(t)M_c + (m + 1)(\sigma_e - \sigma_e^*)}{2A(t)M_c} \right]^{1/(m + 1)}.
\]  

(7)

As mentioned above, \(A(t)\) is the function of time. The scope of the plastic zone varies with time and finally tends to be stable. The stabilized radius of the plastic zone thus should be considered in determining the proper sealing depth.

Moreover, the methane self-emission zone varies with the time and is closely related to the coal rank. According to the National Work Safety Industry Standards of China (AQ1018-2006) which has been strictly derived and proved, the radius of the methane self-emission zone can be calculated by the following two equations:

For the low-grade metamorphism coal, we have\(^{33}\)

\[
R_e = 0.8087T^{0.55}.
\]  

(8)

For the high-grade metamorphic coal, we have\(^{33}\)

\[
R_e = (13.85 \times 0.0183T)/(1 + 0.0183T),
\]  

(9)

where \(R_e\) is the radius of the methane emission zone; \(T\) is the methane emission time, which starts from the exposure of the roadway wall.

3.2.2 | Technical method

The successful use of the above-mentioned theoretical method is based on the knowledge of the geological conditions which are generally very complex. Thus, a technical method should also be developed to help to determine proper sealing depth.

The coal surrounded the roadway exhibits different mechanical status which can lead to the varied resistance when drilling an in-seam borehole. It has been proved that the imported oil pressure of the hydraulic motor (which makes the drill bit rotating clockwise to break the rock) and the penetration velocity can be used as the index to evaluate the mechanical status of coal surrounded the roadway.\(^{34}\)

Figure 5 shows the typical monitoring data of the penetration velocity and imported oil pressure during the in-seam borehole drilling. It is clear that the penetration velocity and the imported oil pressure vary with the drilling depth of the in-seam borehole. The imported oil pressure increases rapidly and the penetration velocity decreases simultaneously at the depth of approximately 13-17 m, indicating that the coal in this zone can generate more resistance for borehole drilling. This phenomenon is mainly because the coal in this zone is easy to deform bearing the certain in-situ stress, thus increasing the resistance applied on the drilling rod, and then resulting in the rapid increase of the imported oil pressure and decreases of the penetration velocity.\(^{34}\) Among the failure zone, the plastic zone and the visco-elastic zone around the roadway, the plastic zone has been proved to be the most potential one to deform bearing the certain in-situ stress. Particularly, the imported oil pressure basically unchanged at the depth of approximately 17-25 m, indicating that the drilling resistance also basically unchanged and no more failing coal generated resistance to the drilling rod in this area. Thus, it can be deduced that the inner boundary of the plastic zone of the coal surrounded the roadway is 17 m.

![FIGURE 5 Penetration velocity and imported oil pressure modified after\(^{34}\)](Image 310x80 to 548x270)
4 | FIELD TESTS AND VERIFICATION

4.1 | Pre-drainage enhancements of in-seam boreholes

As discussed above, both the borehole space and the sealing performance influence the CMM drainage efficiency. Thus, the pre-drainage enhancements of in-seam boreholes are based on these two aspects.

First, the sieve tubes made of high-density polyethylene has been used to maintain the borehole space during the scheduled pre-drainage period. The sieve tube is usually 30-40 mm in diameter, that is, the radius is far smaller than the borehole radius. There are many holes in the tube wall, whose radius ranges from 5 to 10 mm. The sieve tubes can be put into the borehole during drilling or after drilling. If the borehole begins to shrinkage, the sieve tubes can bear a certain compressional force and maintain the borehole space. Then, the CMM can flow through the tubes to the drainage system.

Second, determining the proper sealing depth based on the comprehensive approach. Outburst-prone coal seams are usually with low permeability, and they need high borehole suction for pre-drainage. The borehole suction is closely related to the sealing performance. A high drainage negative pressure can be maintained only when the fractures around the borehole and the roadway were well filled. If the sealing performance is poor, increasing suction will induce more air leakage into the borehole and hence reduce the methane concentration. Conversely, reducing suction may be beneficial to the methane concentration but it will reduce the methane flow flux. Sealing the borehole in a proper depth with pressured cement grout, the interior space of the borehole can maintain a relatively high negative pressure. Thus, it can be concluded that the improvement in borehole sealing can not only reduce the air leakage into the borehole but also be beneficial to keep a higher suction.

The two improvements in in-seam borehole pre-drainage can be beneficial to extend the effective drainage time and maintain the gas concentration. The efficiency of pre-drainage will be improved, thus maximizing the role of in-seam boreholes in pre-drainage.

4.2 | Field verification

4.2.1 | Test site

The test site concerned in this study is the 715 workface in the Qinan coal mine, which is located in Huaihe City, Anhui Province, China. There are three main minable seams, Nos. 3, 7, and 10 from top to bottom, and all of these seams have an outburst tendency. The 715 workface in No. 7 coal seam is buried at 620 m in average. The coal thickness ranges from 1.4 to 4.0 m, with an average of 2.2 m. The workface is approximately 1000 m in length and 150 m in width. The in-seam boreholes for pre-drainage were designed to be at least 80 m in length and 108 mm in diameter.

No. 7 coal seam is with the most serious outburst hazard. The maximum measured gas pressure at −550 m level in No. 7 coal seam is 3.5 MPa. The gas content ranges from 12.3 to 15.4 m³/t and the original permeability is only 0.00115 mD. The other basic parameters including adsorption properties, proximate analysis, etc. of the No. 7 coal seam are listed Table 1.

4.2.2 | Analysis of the proper sealing depth of in-seam boreholes

In the following, the proper sealing depth for 715 workface was analyzed by the comprehensive approach.

First, the radiuses of the plastic zone and the methane self-emission zone were calculated by using the theoretical method. Based on the geological data, the information about the in-situ stress, strength properties, etc. is obtained. The vertical in-situ stress is approximately 15.5 MPa, and the horizontal in-situ stress is similar to the vertical in-situ stress in value. Thus, the initial in-situ stress can be considered as 15.5 MPa. The strength parameters of No. 7 coal seam used are: long-term shear modulus \( G_\infty = 600 \text{ MPa} \); instantaneous shear modulus \( G_0 = 1200 \text{ MPa} \); angle of initial internal friction \( \varphi = 22^\circ \); cohesion \( c = 3.5 \text{ MPa} \); residual strength \( c^* = 0.6 \text{ MPa} \); coefficient of expansion in plastic zone \( \eta_1 = 1.1 \); coefficient of expansion in breathe zone \( \eta_2 = 1.3 \); and softening coefficient of coal \( M_c = 1.0 \). The diameter of the roadways in the 715 workface is 4.0 m, and the support resistance of the roadway \( p_1 \) is 0.2 MPa. By substituting these parameters into the Equations (6) and (7), the stabilized radius of the plastic zone can be obtained, which is approximately 16.3 m.

Before coal mining of 715 workface, the time for pre-drainage and methane self-emission was approximately 12 months. The No. 7 coal seam is the gas-fat coal which is a low-grade metamorphism coal. Thus, the radius of the

| Parameters | Value | Units |
|------------|-------|-------|
| Adsorption constant, \( a \) | 19.43 | m³/t |
| Adsorption constant, \( b \) | 1.09 | MPa⁻¹ |
| The coefficient of solidity, \( f \) | 0.33 | Dimensionless |
| Initial velocity of gas release, \( \Delta P \) | 12.2 | mmHg |
| Water content, \( M_{wd} \) | 1.465 | % |
| Ash content, \( A_d \) | 17.41 | % |
| Volatile component, \( V_{daf} \) | 29.43 | % |
| Coal real density, \( d_c \) | 1.42 | g/cm³ |
| Coal apparent density, \( d_s \) | 1.33 | g/cm³ |
methane emission zone $R_e$ can be calculated by Equation (8). By substituting the self-emission time into the Equation (8), $R_e$ is obtained, which is approximately 20.6 m. Based on the theoretical method, the practicable range of sealing depth for 715 workface was obtained, which ranges from 16.3 to 20.6 m.

In the following, the technical method was used to further analysis the proper sealing depth. By tracking the drilling process, we found that the resistance applied on the drilling rod and the volume of the drilling cuttings generally increased within the drilling depth of 15-20 m from the opening wall, and the two parameters became lower and relatively stable after drilling across this coal mass. Besides, when installing sieve tubes in the in-seam boreholes, the most difficult or the most resistance stage happened in the depth of 15-18 m from the roadway opening wall. These phenomena indicate that the coal mass, within 15-20 m from the opening wall, failed or/ and collapsed during and after borehole drilling, thus increasing the resistance of borehole drilling and tubes installing.

In summary, the practicable range of sealing depth for 715 workface should range from 15 to 20 m, and the sealing depth of approximately 20 m should be the proper sealing depth.

### 4.2.3 The influence of sealing length on CMM drainage

In order to verify the validity of the comprehensive approach-obtained proper sealing depth, three different sealing depths (ie, 15, 20, and 25 m) were compared. To ensure a fair comparison, the three tested boreholes were with the negative drainage pressure, and the installed sieve tubes were of the same length. Figure 6 illustrates the methane concentrations and methane flow rates of the three test boreholes vs time.

The methane concentrations of all the three test boreholes decrease with time in different descent rates. For the test borehole whose sealing depth is 15 m, the methane concentration decreased sharply from more than 90% to <30% within 85 days. However, the methane concentration can maintain above 40% after drainage approximately 260 days for the other two test boreholes. The methane flow rate of all the three test boreholes also decreases with time in different descent rates. The differences between the methane flow rates of the three test boreholes are not apparent within drainage about 75 days. The methane flow rates of the two test boreholes whose sealing depth are 20 and 25 m can maintain nearly stable in the excess time. However, the methane flow rate of the test borehole whose sealing depth is 15 m continually decreased. It can be found that the methane concentrations and methane flow rates of the two test boreholes whose sealing depth are 20 and 25 m are similar. This phenomenon indicates that the sealing performances of these two boreholes are similar, that is, the sealing depth will not be beneficial to the sealing performance when it exceeds the proper sealing depth. In this case, the sealing depth of 25 m may bring some safety risks as it is longer than the radius of the methane self-emission zone. The field tests prove that the sealing depth of 20 m is proper for the 715 workface.

### 4.2.4 Comparison between naked borehole and sieve tubes-installed borehole

To verify the improvement in CMM drainage induced by maintaining borehole space, the comparison between naked borehole and sieve tubes-installed borehole has been made.

By substituting the parameters (which were provided in Section 4.2.2) of the coal into the Equations (3-5), we can get the shrinkage behavior of borehole space with time, as shown in Figure 7. The displacement of the borehole wall increases with time, and the borehole radius decreases with time. The borehole space was completely filled after approximately 28 days of borehole drilling. As a result, the gas drainage becomes more and more difficult due to the gradual compaction of the borehole space, and finally, almost no methane can be drained from the borehole.

The sieve tubes can bear a certain compressional force and maintain the borehole space. Then the effective time of

**FIGURE 6** Methane concentration and flow rate evolution for different sealing depths

**FIGURE 7** Displacement of the borehole wall and residual radius
CMM pre-drainage can be prolonged. The gas flows of naked boreholes and sieve tubes-installed boreholes are shown in Figure 8. To ensure a fair comparison, all of the test boreholes were sealed with a depth of 20 m.

The gas flows of the four test boreholes decreased sharply from approximately 0.25 to 0.032 m³/min in about 25 days. The gas flows of the naked boreholes were even superior to that of the sieve tubes-installed boreholes in these 25 days. This phenomenon indicates that the borehole space can maintain at least 25 days, and the sieve tubes didn’t play a favorable role in methane drainage in these days.

Then, the gas flows vary greatly in terms of the value and tendency between the naked boreholes and the sieve tubes-installed boreholes. For the naked boreholes, the gas flows decreased continually. The gas flows almost approach to zero after drainage of 70 days. This phenomenon suggests that the naked boreholes were gradually compacted in approximately 70 days. By contrast, for the sieve tubes-installed boreholes, the gas flows remain nearly constant (ie, without obviously decreasing) after drainage of 25 days. Approximately 20 m³ of methane can be drained every day. The field tests proved that the sieve tubes can bear a certain compressional force and maintain the borehole space, resulting in the effective time of CMM pre-drainage be prolonged.

**5 | CONCLUSIONS**

As in-seam boreholes are directly drilled in the coal seams, continuous high efficiency in CMM pre-drainage is expected. However, the common phenomenon in CMM pre-drainage with in-seam boreholes is sometimes disappointing. The borehole sealing performance is one of the main factors that influence the CMM drainage efficiency. This study was conducted to seek a method to improve the sealing performance for high-efficiency CMM drainage. Based on the work completed, the following conclusions are made:

1. The excavation of underground openings (including roadways and boreholes) can generate a large number of fractures in the coal surrounded the roadway, thus influence the sealing performance. A visco-elastic plastic model considering the strain softening and dilatancy was used to analyze the fracture characteristics around the roadway. The surrounding coal of a roadway can be divided into four regions: the failure zone, the plastic zone, the visco-plastic zone, and the uninfluenced zone.

2. A comprehensive approach including the theoretical method and the technical method was developed to determine the proper sealing depth. The basic requirements of the comprehensive approach were discussed. The theoretical method indicates that the proper sealing depth should be longer than the radius of the plastic zone and be shorter than the radius of the methane-self emission zone. Technical method is an essential supplement of the theoretical.

3. A series of field tests were conducted in an outburst-proven coal seam to verify the feasibility of the improved method for high-efficiency CMM drainage. Based on the comprehensive approach, the practicable range of sealing depth for 715 workface should range from 15 to 20 m, and the sealing depth of approximately 20 m should be the proper sealing depth. The validity of the comprehensive approach-obtained proper sealing depth was verified by the analysis of the methane concentrations and methane flow rates of three test boreholes.

4. The sieve tubes made of high-density polyethylene has been used to maintain the borehole space during the scheduled pre-drainage period. If the borehole begins to shrinkage, the sieve tubes can bear a certain compressional force and maintain the borehole space. The effective time of CMM pre-drainage with in-seam boreholes can be prolonged.

5. The two pre-drainage enhancements of in-seam boreholes, including the comprehensive approach to determine the proper sealing depth and the installing of sieve tubes to protect the borehole space, can provide favorable conditions for maximum CMM pre-drainage from outburst-prone coal and maximum utilization of the in-seam boreholes.

**ACKNOWLEDGMENTS**

The authors would like to thank the reviewers for their critical and constructive review of this paper. This research was financially supported by the National Natural Science Foundation of China (No. 51704286) and the Fundamental Research Funds for the Central Universities (No. 2015XKMS008).

**CONFLICT OF INTEREST**

None declared.
REFERENCES

1. Sobczyk J. The influence of sorption processes on gas stresses leading to the coal and gas outburst in the laboratory conditions. Fuel. 2011;90:1018-1023.
2. Beamish BB, Crosdale PJ. Instantaneous outbursts in underground coal mines: an overview and association with coal type. Int J Coal Geol. 1998;35:27-55.
3. Zhou H, Yang Q, Cheng Y, Ge C, Chen J. Methane drainage and utilization in coal mines with strong coal and gas outburst dangers: a case study in Luling mine, China. J Nat Gas Sci Eng. 2014;20:357-365.
4. E.E.S. No, best practice guidance for effective methane drainage and use in coal mines (2010).
5. Frank H, Ting R, Naj A. Evolution and application of in-seam drilling for gas drainage. Int J Min Sci Technol. 2013;23:543-553.
6. Karacan C, Diamond W, Schatzel S. Numerical analysis of the influence of in-seam horizontal methane drainage boreholes on longwall face emission rates. Int J Coal Geol. 2007;72:15-32.
7. Zhou H, Dai H, Ge C. Quality and quantity of pre-drainage methane and responding strategies in Chinese outburst coal mines. Arab J Geosci. 2016;9:445.
8. Junxiang Z, Bo L, Yuning S. Dynamic leakage mechanism of gas drainage borehole and engineering application. Int J Min Sci Technol. 2018;28:505-512.
9. Lu T, Yu H, Zhou T, Mao J, Guo B. Improvement of methane drainage in high gassy coal seam using waterjet technique. Int J Coal Geol. 2009;79:40-48.
10. Xu C, Fu Q, Wang K, Yuan L, Zhang X, Wang S. Effects of the loading methods on the damage-permeability aging characteristics of deep mining coal. J China Univ Min Technol. 2018;47:197-205.
11. Ni G, Cheng W, Lin B, Zhai C. Experimental study on removing water blocking effect (WBE) from two aspects of the pore negative pressure and surfactants. J Nat Gas Sci Eng. 2016;31:596-602.
12. Liu Q, Cheng Y, Yuan L, Tong B, Kong S, Zhang R. CMM capture engineering challenges and characteristics of in-situ stress distribution in deep level of Huainan coalfield. J Nat Gas Sci Eng. 2014;20:328-336.
13. Liu C, Li S, Yang S. Gas emission quantity prediction and drainage technology of steeply inclined and extremely thick coal seams. Int J Min Sci Technol. 2018;28:415-422.
14. Zhou F, Li J, Ze X, Liu Y, Zhang R, Shen S. A study of the second hole sealing method to improve gas drainage in coal seams. J China Univ Min Technol. 2009;6:764-768.
15. Zhai C, Xiang X, Yu X, Peng S, Ni G, Li M. Sealing performance of flexible gel sealing material of gas drainage borehole. J China Univ Min Technol. 2013;6:982-998.
16. Fan F, Zhang F, Qin R. Study on new borehole sealing device of gas drainage borehole along seam. Coal Sci Technol. 2013;41:73-75, 80.
17. Wang Z, Wu W. Analysis on major borehole sealing methods of mine gas drainage boreholes. Coal Sci Technol. 2014;42:31-34, 103.
18. Liu Q, Cheng Y, Jin K, Tu Q, Zhao W, Zhang R. Effect of confining pressure unloading on strength reduction of soft coal in borehole stability analysis. Environ Earth Sci. 2017;76:173.
19. Si G, Jamnikar S, Lazar J, et al. Monitoring and modelling of gas dynamics in multi-level longwall top coal caving of ultra-thick coal seams, part I: borehole measurements and a conceptual model for gas emission zones. Int J Coal Geol. 2015;144-145:98-110.
20. Si G, Shi J, Durucan S, et al. Monitoring and modelling of gas dynamics in multi-level longwall top coal caving of ultra-thick coal seams. Part II: numerical modelling. Int J Coal Geol. 2015;144-145:58-70.
21. Eyw R, Cook N. Deformation and fracture around cylindrical openings in rock—I. Observations and analysis of deformations. Int J Rock Mech Min Geomech 1990;27:387-407. Abstracts, Elsevier.
22. Fuenkajorn K, Daemen J. Sealing of Boreholes and Underground Excavations in Rock. London: Springer Science & Business Media; 2012.
23. Labuz JF, Zang A. Mohr-Coulomb failure criterion. Rock Mech Rock Eng. 2012;45:975-979.
24. Badr S, Ozbay U, Kiefler S, Salamon M. Three-dimensional strain softening modeling of deep longwall coal mine layouts. In: Andrieux P, Brummer R, Detournay C, Hart R, eds. Third International Symposium on FLAC and FLAC3D Numerical Modelling in Geomechanics. Sudbury, ON: Taylor & Francis; 2003:233-239.
25. Pedersen R, Simone A, Sluys L. An analysis of dynamic fracture in concrete with a continuum visco-elastic visco-plastic damage model. Eng Fract Mech. 2008;75:3782-3805.
26. Hsiung B-CB. A case study on the behaviour of a deep excavation in sand. Comput Geotech. 2009;36:665-675.
27. Kang J, Zhou F, Liu C, Liu Y. A fractional non-linear creep model for coal considering damage effect and experimental validation. Int J Non Linear Mech. 2015;76:20-28.
28. Hudson J, Harrison J, Popescu M. Engineering rock mechanics: an introduction to the principles. Appl Mech Rev. 2002;55:72.
29. Liu Q, Cheng Y, Yuan L, Fang Y, Shi D, Kong S. A new effective method and new materials for high sealing performance of cross-measure CMM drainage boreholes. J Nat Gas Sci Eng. 2014;21:805-813.
30. Xiang X, Zhai C, Xu Y, Xu X, Xu J. A flexible gel sealing material and a novel active sealing method for coal-bed methane drainage boreholes. J Nat Gas Sci Eng. 2015;26:1187-1199.
31. Cheng Y, Wang H, Wang L, et al. Theories and Engineering Applications on Coal Mine Gas Control. Xuzhou: China University of Mining and Technology Press; 2010.
32. Zhang Q, Jiang B-S, Wang S-L, Ge X-R, Zhang H-Q. Elasto-plastic analysis of a circular opening in strain-softening rock mass. Int J Rock Mech Min Sci. 2012;50:38-46.
33. State Administration of Work Safety. The predicted method of mine gas emission rate (AQ 1018-2006), in Beijing; 2006.
34. Zhang N, Yuan L, Han C, Xue J, Kan J. Stability and deformation of surrounding rock in pillarless gob-side entry retaining. Saf Sci. 2012;50:593-599.
35. Zhang J, Bai M, Roegiers JC. Dual-porosity poroelastic analyses of wellbore stability. Int J Rock Mech Min Sci. 2003;40:473-483.

How to cite this article: Liu Q, Zhou H, Cheng Y, Shu L, Ullah B. An improved method for high-efficiency coal mine methane drainage: Theoretical analysis and field verification. Energy Sci Eng. 2018;6:739–748. https://doi.org/10.1002/ese3.248