INTRODUCTION

As a substitute for coal and oil in power generation, coalbed methane (CBM) also known as coal seam gas (CSG) is a form of natural gas extracted from both low-rank and high-rank coalbeds. Currently, the commercial extraction of CBM is well established in many countries all over the world, such as the USA, Australia, China, Canada, and Poland. According to statistics, the estimated CBM resources in China are around 31.54 Tm³ and throughout the past decades, CBM production in China has dramatically increased up to 7.02 Bm³ with an annual growth rate of 8.2% in 2017, in which over 70% CBM is extracted from underground coal mines. Meanwhile, with the mining depth increasing, China has suffered the world’s highest risk of coal and gas outburst disasters owing to the low permeability of coalbeds and the high gas content. Chinese State Administration of work safety reported that there were totally 164 gas accidents, killing about 955 miners from 2013 to 2016. Thus, insisting on gas extraction before coal mining not only can eliminate the
danger of coal and gas outbursts during coal mining period, but also provides clean energy and reduces greenhouse gas emissions.14,15

Coalbed methane gas-in-place (GIP) estimation is one of the most crucial steps for CBM extraction. As an essential parameter determining coalbed gas content and kinetic properties of coal, gas pressure is the force generated by thermal motion of gas molecules in coal seam pores and is always perpendicular to the pore wall.16,17 Additionally, coal and gas outbursts probably happen in the coal seams with the gas pressure exceeding 0.74 MPa in China.18 To obtain the accurate gas pressure value, scholars in Germany and Poland applied the relations between gas pressure and the rate of gas desorption for calculating the gas pressure in coalbed with Janas’s equation.19,20 Based on Langmuir’s equation, scholars in Ukraine also indirectly measured the gas pressure by considering gas content and coal adsorption coefficients (α and β).21 In China, Wang and Xian22 proposed the relations between geostress, geothermal, and the coalbed permeability in the unidimensional steady flow, and then established an analytical formula of gas pressure in deep coal mining. Xu and Xian23 later discussed the theoretical computing method of gas pressure in coal seams. However, the indirect methods were just used in cases where hard to directly measure the gas pressure owing to the complex geological conditions and the calculation deviations brought about other parameters. The gas pressure was also measured directly by drilling boreholes in Spain.24,25

In the direct measurement process of gas pressure, a borehole is first drilled into the scheduled test location in coal seam, then a copper tube drawn out from the gas chamber in borehole. After sealing the borehole, gas pressure values can be recorded with a pressure gauge till the readings are stable.26 Thus, the quality of hole sealing determines the success of gas pressure measurement or not. The early sealing methods of only using clay, cement, or rubber rings have been eliminated on account of shortcomings of a short sealing distance and the gas leakage from the broken zone around borehole.27-30 Although polyurethane shows the advantages of high expansibility, rapid expansion, and convenience, it displays the weak cementing power and the low compressive strength. Based on the perspective of solid sealing liquid and liquid sealing gas, Zhou et al.25,31,32 proposed the sealing technology of expandable capsule-viscous liquid, significantly improving the hole-sealing effect. However, the expandable capsule is hardly pulled out for recycling once the borehole collapses. Then, a pressurized sealing technology was widely carried out in many coal mines using polyurethane to plug the two ends of borehole and grouting pressurized cement mortar into the inside,33,34 now recommended as one of primary sealing technologies in gas pressure measurement. Unfortunately, Wang and Wu30 considered the pressurized sealing technology just nominally existed in some coal mines owing to the lack of further researches on selections of the initial sealing position and the grouting pressure by the comparative analysis of major sealing methods of gas extraction borehole in China. Zhou and Li35 once presented the second sealing method using the superfine cement to further boost the sealing effect. Because of the high price of superfine cement and a long measurement cycle, this sealing method isn’t yet widespread so far.

By limitations of coalbed occurrences (the coalbed dip angle and the aquifer) and other geological conditions, the horizontal boreholes are inevitably drilled for gas pressure measurement sometimes. However, it is more intractable to seal the long horizontal boreholes. Owing to the auto-shrinkage of cement mortar, a leakage gap would emerge between the hole wall and the cement surface. Here is the case in Liulong coal mine (Guizhou Prov.). To measure the original gas pressure of 7# coal seam, 1076 drainage tunnel located between 7# coal seam and 3# coal seam was selected as the test site. We clearly interpreted the various influencing factors on the horizontal hole sealing, including the auto-shrinkage effect of cement material on the gas leakage, the initial sealing position, and the grouting pressure. Next, a pressurized sealing technology by drilling a reducing-nipple hole was successfully applied in this measurement test. The results show that this method is worthy to be popularized for the horizontal hole sealing but not limited to this situation in virtue of tight sealing effects and simple operation.

2 | AUTOSHRINKAGE EFFECT ON HOLE SEALING

In 1934, Layman discovered the auto-shrinkage phenomenon, which generally means the decrease in the macroscopic volume caused by the continual hydration of cementing materials to generate the self-drying after the initial solidification in the condition of a constant temperature and an isolated humidity. And the auto-shrinkage effect universally exists in any cement mortar, regardless of the water-cement ratio.37,38 To investigate the impact of auto-shrinkage on horizontal hole sealing, the auto-shrinkage tests of cement mortar with different water-cement ratios were conducted. Then the model of gas flow in the gap between sealing medium and holewall was established to discuss this gas leakage effect.

2.1 | Autogenous shrinkage tests of cement specimen

2.1.1 | Tests

P•O 42.5 Portland cement produced by Guiyang Conch Co. Ltd. was selected in the early-age auto-shrinkage test. The density of cement is 3.05 g/cm³ and the measured compressive strength is 45.8 MPa. Here, we just focused on the impact of
water-cement ratio on autoshrinkage, so the contents of sand and cement accelerator were, respectively, controlled at 20% and 5% in every group of cement specimen. Table 1 displays the mixture ratios of cement mortar.

We adopted a transparent plexiglass tube (Φ = 25 × 300 mm) as the mould. To ensure the cement mortar produced free shrinkage deformation without external constraints during the test, we evenly smeared the tube inwall with a thin layer of silicone oil. Then the three cement specimens (C1, C2, and C3) with different mix proportions were successively injected into the tube under the conditions of the relative humidity of 60 ± 5% and the temperature of 20 ± 3°C. We also embedded two copper probes into the cement mortar at the distance of 10 mm to both ends of the mould, and then sealed them with melted paraffin. Each cement specimen was gently rotated in clockwise direction every 5 min in order to avoid the bleeding. The height of dial indicator was adjusted by adjustment screws, so that the end was aligned with the buried probe. We eventually recorded the readings of dial indicator, which is the specimen length at different ages of hydration. The schematic diagram of autoshrinkage test is shown in Figure 1.

The autoshrinkage of cement specimen can be calculated with the following equation.

\[ S_t = L_0 - L_t \]  

where \( S_t \) is the cement autogenous shrinkage at the age of \( t \); \( L_0 \) is the initial length of specimen; \( L_t \) is the length of specimen at the age of \( t \); and \( L_b \) is the gauge length of specimen.

### 2.1.2 Results

As shown in Figure 2, the three cement specimens all shrank fast from the initial setting time to the age of 1 d and the autoshrinkage values of specimens (C1, C2, and C3) in 1 d, respectively, accounted for 74%, 70%, and 56% of the total shrinkage amount in 7 d. It is mainly because the hydration reaction of specimens in the first 24 h is so intensive that the internal humidity of cement decreases fast under the action of cement accelerator, resulting in a significant self-drying and a sharp shrinkage. Meanwhile, the shrinkage amount of specimen in 7 d increased from 332 to 645 µm when the water-cement ratio was reduced from 0.5 to 0.3. It indicates that the specimen with the lower water-cement ratio has a greater potential energy of autoshrinkage. When the water-cement ratio is small, the content of internal free water supplying continuous hydration of cement is less, thus the humidity decreasing quickly. Besides, the refinement degree of cement pores is relatively high and the critical radius is also reduced, so the amount of autoshrinkage caused by self-drying would increase. However, the strength of cement mortar is weakened with the water-cement ratio rising based on the water-cement ratio law. In order to relieve the autoshrinkage impact and meanwhile to ensure a sufficient strength of cement mortar, P•O 42.5 cement mortar with the water-cement ratio of 0.5 was selected for sealing boreholes.

### 2.2 Gas flow model in the gap

In the process of gas pressure measurement in horizontal borehole, gas often gushes out through the gap caused by the autoshrinkage of sealing medium. The performance of hole sealing is mainly evaluated by the amount of gas leakage. By considering the autoshrinkage effect and the gravity of cement, a simplified theoretical model of gas leakage in an eccentric ring gap was proposed to calculate the amount of gas leakage by assuming the following conditions.

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**TABLE 1** Mix proportions of cement mortar/kg/m³

| Code | Cement  | Sand   | Water  | Cement accelerator | W/C |
|------|---------|--------|--------|--------------------|-----|
| C1   | 1477    | 480    | 443    | 120                | 0.3 |
| C2   | 1370    | 480    | 550    | 120                | 0.4 |
| C3   | 1280    | 480    | 640    | 120                | 0.5 |

**FIGURE 1** Schematic diagram of autoshrinkage tests of cement specimen

**FIGURE 2** The autoshrinkage amount of specimens with different W/C ratios
1. Gas flow in a narrow gap is regarded as the steady laminar flow.
2. There is no relative motion in the gap.
3. The absorption of coalbed to gas and the gravity of gas are both neglected.

As shown in Figure 3, gas flows in the eccentric ring gap under the pressure difference between inside and outside of borehole. The eccentricity and the width of gap are $\delta$, $h$, respectively. As the gap width is too small ($r_1 \approx r_2 = r$), we regarded the infinitesimal flow in the eccentric ring gap as the parallel plate flow.\(^{40,41}\) Thus, gas flow equation in the gap was derived according to the equilibrium theory of forces and Newton’s law of friction as follows.

$$dQ = \frac{h^3 \Delta P}{12 \mu L} \, db,$$  \hspace{1cm} (2)

where $dQ$ is the gas flow differential; $db$ is the differential of arc length; $\Delta P$ is the pressure difference between inside and outside of borehole; $h$ is the width of gap; $\mu$ is the kinetic viscosity, and $L$ is the length of sealing medium. Then, the following equation can be written as follow by substituting $db = rd\theta$ into equation 2.

$$dQ = \frac{P_1 - P_2}{12 \mu L} h^3 r d\theta,$$  \hspace{1cm} (3)

where $P_1$ is the gas pressure; $P_2$ is the atmospheric pressure; $\theta$ is the angle differential and $r$ is the radius of borehole.

Thus, the amount of gas leakage was obtained by the integration in the angle range of $0 \sim 2\pi$ as follows.

$$Q = \frac{\pi D \, (P_1 - P_2)}{12 \mu L} h_0^3 \left(1 + 1.5 \delta^2\right)$$  \hspace{1cm} (4)

where $D$ is the diameter of borehole; $h_0$ is the gap width in the concentric ring model and $\delta$ is the relative eccentricity of sealing medium. It shows when the eccentricity reaches the maximum ($\delta = 1$), the gas leakage amount in the eccentric ring gap is theoretically 1.5 times larger than that in the concentric ring gap.

### 3 | ANALYSIS OF THE INITIAL SEALING POSITION

After the excavation of tunnel, the equilibrium of stresses of surrounding rock has been broken, successively forming the three zones (stress relief zone, concentrated stress zone, and original stress zone) around tunnel.\(^{42}\) These zones can be further divided into three regions: the fracture zone (I), the plastic zone (II), and the elastic zone (III) as shown in Figure 4. If the sealing length is not enough to exceed the scope of the plastic zone, a part of gas in measuring chamber would leak through the developed fissures to connect to the atmosphere, causing the failure of gas pressure measurement. Whereas the whole section sealing not only wastes a lot of material, also is hardly achieved by the limitation of geological conditions. Thus, the selection of the initial sealing position should be discussed here.

#### 3.1 | Theoretical solution of the plastic zone around tunnel

To calculate the theoretical radius of the plastic zone, a simplified model\(^{43}\) was proposed by assuming the following conditions.

1. The surrounding rock is an isotropic and homogeneous material submitting Mohr-coulomb criterion.
2. The stress-strain relation is divided into the linear elastic deformation, the plastic deformation caused by strain softening and the residual deformation.
3. The tunnel is in the field of in situ stress of $P$ and the lateral stress coefficient $\lambda = 1$.
4. The model is based on the plain strain assumption.

The equation of static equilibrium can be given as follows in polar coordinate system.

$$\frac{d\sigma_r}{dr} + \sigma_r - \sigma_\theta = 0.$$  \hspace{1cm} (5)

And the geometric relation is shown as follows.
where $\sigma_r$, $\sigma_\theta$ are the radial stress and the tangential stress of surrounding rock, respectively; $\varepsilon_r$, $\varepsilon_\theta$ are the radial strain and the tangential strain, respectively; $u$ is the radial displacement and $r$ is the distance from a point to the tunnel center.

The yield of surrounding rock in the elastic deformation stage submits Mohr-coulomb criterion, described as follows.

$$\sigma_1 = \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 + \sigma_c,$$

where $\sigma_1$ and $\sigma_3$ are the tangential stress and the radial stress of surrounding rock, respectively; $\varphi$ is the friction angle of surrounding rock; and $\sigma_c$ is the uniaxial compressive strength.

At the stage of strain softening, the friction angle of rock $\varphi$ remains constant, but the rock strength decreases with the deformation development. The softening condition can be presented as follows.

$$\sigma_1^R = \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 + \sigma_c^R,$$

where $\sigma_c^R$ is the compressive strength of rock in the strain softening zone, which is a variable.

The stress-strain relation can be expressed using the model of three spans of line.

$$\sigma_c^R = \sigma_c - M_0 (\varepsilon_\theta^R - \varepsilon_\theta^R),$$

where $M_0$ is the strain softening modulus; and $\varepsilon_\theta^R$, $\varepsilon_\theta^R$ are the tangential strain at the elastic-plastic interface, and the tangential strain in the plastic zone, respectively.

The rock strength in the residual deformation zone is described as follows.

$$\sigma_1^r = \frac{1 + \sin \varphi}{1 - \sin \varphi} \sigma_3 + \sigma_c^r,$$

where $\sigma_c^r$ is the residual strength of rock.

By considering the shear dilatancy of surrounding rock, the nonassociated flow rule is adopted as follows.

$$\varepsilon_3^P + \alpha \varepsilon_3^P = 0,$$

where $\alpha$ is the dilatancy coefficient; and $\varepsilon_3^P$, $\varepsilon_3^P$ are the increment of radial strain in the plastic zone, and the increment of tangential strain in the plastic zone, respectively.

Substituting Mohr-coulomb criterion into the equation of static equilibrium, the following equation is obtained as follow.

$$\frac{d\sigma_c^P}{dr} - \frac{2 \sin \varphi}{1 - \sin \varphi} \sigma_c^P = \sigma_c^P.$$

By putting the boundary conditions ($r = a$, $\sigma_c^P = 0$) into the equation, the radius of plastic zone can be obtained by the assumption of an ideal elastoplastic mechanical model as follows.

$$R = a \left[ \frac{2 \sin \varphi + \sigma_c (1 - \sin \varphi)}{\sigma_c} \right]^{\frac{1 - \sin \varphi}{2 \sin \varphi}},$$

where $a$ is the equivalent radius of tunnel; $\sigma_c$ is the uniaxial compressive strength; $\varphi$ is the friction angle of surrounding rock; and $P$ is the stress of primary rock.

One thousand and seventy-six drainage tunnel is located in the siltstone roof of #7 coal seam. The equivalent radius of the tunnel is 2 m and the buried depth is about 360 m. The friction angle of the siltstone is 36°, and the cohesion is 3.62 Mpa. Thus, the theoretical plastic zone radius of 1076 drainage tunnel is calculated about 2.32 m with Equation 13.

### 3.2 Borehole peering

In order to actually observe the surrounding rock breakage of 1076 drainage tunnel, SYS (B) electronic peering instrument which can automatically adjust the lightsource brightness to obtain sharp images according to properties of the measured object, was applied in the borehole. The horizontal peephole ($\Phi = 32$ mm; $L = 6$ m) was arranged in the middle of the tunnel rib, and the image acquisition was conducted along the peep-hole length every 0.5 m as a monitoring point. The breakage degree of rock was mainly determined by macro and micro fractures and the observation results are shown in Figure 5.

The observation results indicated the shallow surrounding rock within 1.5 m was seriously broken and the damage degree was gradually weakened with an increasing depth of borehole. Additionally, a few micro fractures still existed 2.5 m away from the tunnel. However, the surrounding rock about 3 m away from the tunnel was quiet intact. Therefore, it was recommended that the initial sealing position should be started 3 m away from the tunnel at least.

### 4 NUMERICAL ANALYSIS FOR GROUTING PRESSURE

For the pressurized sealing technology by plugging two ends and grouting inside, the grouting pressure directly affect the diffusion radius of cement mortar. When grouted into borehole, cement mortar continually spreads around until filling up the borehole. Next, it begins to seep into fissures around borehole and spreads deeper under the driving of grouting pressure. The difference between the grouting pressure and the pore pressure is the driving force to promote the diffusion of cement mortar.
However, the pore water pressure, the molecular attraction, and the particle friction resist the mortar motion. Along with the linear loss of grouting pressure, the mortar diffusion gradually slows down till reaching the maximum of the diffusion range.

4.1 | Governing equations

To investigate the effect of the grouting pressure on the cement diffusion, the following assumptions were considered: (a) the rock strata are isotropic and homogeneous, experiencing elastic deformation; (b) the cement mortar seepage in fractures satisfies Darcy’s law; (c) the cement mortar is regarded as the incompressible fluid, only flowing through rock fractures in the grouted section; and (d) the injection pressure on the borehole boundary is equivalent to the operating pressure of pump.

4.1.1 | Mortar seepage

Thus, the fluid motion equation can be expressed as follow.

\[ v = -\frac{k}{\mu} (\nabla P + \rho g \nabla D), \]  \hspace{1cm} (14)

where \( v \) is the seepage velocity, m/s; \( k \) is the rock permeability, m\(^2\); \( \mu \) is the mortar viscosity, Pa\( \cdot \)s; \( P \) is the grouting pressure, MPa; \( \rho \) is the mortar density, kg/m\(^3\); \( g \) is the acceleration of gravity, m/s\(^2\); and \( D \) is the vertical coordinate.

The continuity equation of mortar seepage is shown as follows.

\[ \frac{\partial (\rho \varphi)}{\partial t} + \nabla \cdot (\rho v) = \rho q, \]  \hspace{1cm} (15)

where \( \varphi \) is the rock porosity, %; \( q \) is the fluid volume and \( t \) is time, seconds.

Substituting Equation 15 into Equation 14, the relation between the grouting pressure and the fluid density can be obtained as follows.

\[ \frac{\partial (\rho \varphi)}{\partial t} + \nabla \cdot \rho \left[ -\frac{k}{\mu} (\nabla P + \rho g \nabla D) \right] = q. \]  \hspace{1cm} (16)

And the governing equation of the mortar seepage can be defined as follows.

\[ S \cdot \frac{\partial P}{\partial t} + \nabla \cdot \left[ -\frac{k}{\mu} (\nabla P + \rho g \nabla D) \right] = \rho q. \]  \hspace{1cm} (17)

where \( S \) is the storage modulus.

4.1.2 | Rock deformation

Based on the assumption of rock experiencing the elastic deformation, the equilibrium equation of stress is expressed as follows.

\[ \sigma_{i j} + F_i = 0, \]  \hspace{1cm} (18)

where \( \sigma_{i j} \) is the stress, and subscripts \( i \) and \( j \) represent the main directions; \( F_i \) is the body force. Moreover, the geometric equation can be described as follows.

\[ \epsilon_{i j} = \frac{1}{2} \left( u_{i,j} + u_{j,i} \right), \]  \hspace{1cm} (19)

where \( \epsilon_{i j} \) is the strain component and \( u_i \) is the displacement in the \( i \)-direction. Then, the constitutive equation is expressed as follows according to Hooke’s law.

\[ \sigma_{i j} = 2G\epsilon_{i j} + \frac{2G\theta}{1-2v} \epsilon_{i j} \delta_{i j} - \beta_j P_j \delta_{i j} - \beta_m P_m \delta_{i j}. \]  \hspace{1cm} (20)
where $G$ is the rock shear modulus, MPa; $E$ is the rock Young’s modulus, MPa; $\mu$ is the Poisson’s ratio; $\varepsilon_v$ is the volumetric strain; $\delta_{ij}$ is the Kronecker variables; $P_f$ and $P_m$ are the gas pressures on the fracture and on the matrix, respectively, MPa; $\beta_f$ and $\beta_m$ are the Biot coefficients of the fracture and the matrix, respectively.

By combining Equations 18~20, the Navier equation for rock deformation is obtained as follows.

$$Gu_{ij} + \frac{G}{1-2\mu}u_{ijj} - \beta_f P_f - \beta_m P_m + F_i = 0. \quad (21)$$

### 4.2 Coupled model

For the hole sealing test, 1076 drainage tunnel was selected. Based on the geological conditions, the diffusion radius of cement mortar was simulated under different grouting pressures using COMSOL multiphysics numerical software. Combining solid mechanics and fluid-structure interaction physics, the total geometric size of the model is $5 \times 24$ m, the average dip angle of strata is $30^\circ$, and the diameter of borehole is $100$ mm, as shown in Figure 6. Owing to the buried depth of about $360$ m, the stress of $9$ MPa is applied on the top boundary of model to simulate the gravity of the overburden strata. Besides, the bottom boundary of the model is fixed, and the roller boundary is adopted on the model lateral. Table 2 lists the parameters in the simulation, which are obtained from previous test reports of Liulong coal mine.

### 4.3 Numerical results

The relation between the grouting pressure and the diffusion radius is presented in Figure 7. Under the same grouting pressure, the diffusion radius of cement mortar varies with the permeability of rock stratum, and cement mortar spreads more easily on the interface of different strata owing to the developed fissures occurrence. The diffusion radius in limestone is the largest, while that in mudstone is the narrowest. Figure 8 indicates the diffusion radius of mortar would be enlarged with the grouting pressure increasing. When the grouting pressure is up to $4$ MPa, the cement mortar no more diffuses obviously, although the
pressure continually rises. Additionally, the cement mortar mainly spreads in limestone and siltstone having high permeability and porosity. For mudstone, the diffusion radius hardly increases with the grouting pressure rising. An exorbitant grouting pressure not only proposes for a higher requirement of the pump power, but also possibly breaks through the sealing of polyurethane foam, and even results in more splitting fissures around borehole, bringing about more difficulties for the hole sealing. Thus, the threshold value of grouting pressure, 4 MPa, is suitable in 1076 drainage tunnel.

5 | RESULTS AND DISCUSSION

5.1 | Introduction to Liulong coalmine

Liulong coal mine is located in the east of Liupanshui coalfield, (Pingzhi town, Liuzhi special district, Guizhou Prov. China 553400), and its production capacity is about 300 thousand tons of meager-lean coal annually. Nowadays, the coalmine is recovering the three coal seams of Permian Longtan Formation, 7# coal seam of which is the main owing to storage stability with the average thickness and dip angle of approximately 6.4 m, 32°, respectively. Since the shaft area is situated in the junction area of tectonic forces (between the northeastern flank of Liuzhi syncline and the ridge of Meizi anticline), small closed faults are well developed in the roof of 7# coal seam. Consequently, the permeability of 7# coal seam is extremely low. According to 2012 identification results, the maximum of relative gas emission rate reaches 46.37 m³/t, the initial gas emission index (ΔP_max) is 36 mmHg, and Protodyakonov coefficient (f) of 7# coal seam is 0.18. Undoubtedly, Liulong coalmine faces a high risk of coal and gas outburst during the production period. However, the gas pressure of 7# coal seam could not be always accurately measured by the limitation of sealing method (Figure 9).
5.2 Introduction to gas pressure measurement

According to the Chinese industry standard for safety production (AQ1047-2007), the preferred locations of gas pressure measurement should be crosscuts and rock roadways with intact rock and no faults, fractures, or other geological structures near the measurement points, and the distance of uncovering coal seam location between any two measurement sites should be greater than 20 m. Moreover, measuring boreholes should not be drilled in aquifers, caverns, or other man-made pressure-relief areas, and the distance between boreholes and these geological structures should be greater than 50 m. By the mining disturbance of other
panels, we had no alternative but to select 1076 drainage tunnel for the original gas pressure determination of 7# coal seam. The three measurement boreholes of \( P_1, P_2, \) and \( P_3 \) (shown in Figure 10) were, respectively, drilled 5 m, 57 m, and 145 m away from the open-cut off cut to avoid fault structures. The dip angles of boreholes were 2°, 6°, and -12°. Before It is always failed to seal nearly horizontal boreholes by using the conventional methods, because a crescent gap called the water-line would be remained after the cement shrinkage. Then the gap would connect with rock fissures, thus gas leakage channels formed. To solve this problem, an eccentric reducing-nipple drilling technology was combined with the pressurized sealing to block gas leakage from the water line.

Firstly, a big drill bit (\( \Phi = 94 \text{ mm} \)) was adopted to penetrate the roof strata until 5 m away from 7# coal seam. After withdrawing drill rods, we replaced the drill bit with a small one (\( \Phi = 75 \text{ mm} \)) and kept on drilling till penetrating the coal seam 2 m. Then we utilized the air pressure to clean up water and debris in the borehole. Before a copper tube (\( \Phi = 12.7 \text{ mm} \)) placed into borehole as gas conduction, we drilled sieve pores on the one end and welded with a baffle to prevent excessive cement mortar from seeping into the gas chamber. Afterwards, two pairs of polyurethane were, respectively, fixed on both sides of the tube and were rapidly sent into borehole with the tube. It must be noted that one pair of polyurethane should be placed at least 3 m away from the orifice of borehole to exceed the plastic zone scope of tunnel. After the polyurethane foam expansion and solidification, we grouted P•O 42.5 cement mortar with the water-cement ratio of 0.5 to seal the entire borehole. The grouting pressure is 4 MPa to ensure that the cement mortar could effectively seep and seal fissures around borehole. Finally, we installed ball valves and \( CPD8M\)-type electronic determinator to record gas pressure values after the initial setting of cement (24 hours). The specific implementation scheme is presented in Figure 11.

### 5.3 Analysis of test results

The process of gas pressure recording was performed by adhering to the Chinese industry standard for safety production (AQ1047-2007), which stipulates only when the pressure value remains a constant (<0.015 MPa) for 3 days, can the gas pressure determination finish. Thus, we set up a program to record gas pressure values every 2 hours using \( CPD8M\)-type electronic determinator which can continually work for more than 1 month. Eventually, we compared and discussed the measuring results with the previous values. The specific sealing parameters are shown in Table 3 and the build-up curves of gas pressure are presented in Figure 12.

As shown in Figure 12, by combining the eccentric reducing-nipple hole drilling with the pressurized sealing technology, we all successively measured the gas pressure of 7# coal seam in these three test sites. The pressure values of \( P_1, P_2, \) and \( P_3 \) borehole eventually reached up to 1.52, 1.38, and 0.95 MPa after 23, 17, and 13 days, respectively. When the initial sealing position starts from the orifice of borehole, the gas pressure of \( P_2 \)-measuring site is 1.38 MPa, which is lower than that of \( P_1 \)-measuring site. It is mainly because the sealing depth does not exceed the fracture zone, and thus a little gas flows out. When the grouting pressure decreases to 2 MPa, the gas pressure of \( P_3 \)-measuring site is 0.95 MPa, which indicates that the effect of grouting pressure on hole sealing is larger than the initial sealing position. However, the previous measuring result of \( P_0 \) is 0.56 MPa using the ordinary grouting sealing method. The practice has proved that a water-line formed by autoshrinkage of cement mortar is the main leakage channel, which directly causes the failure of gas pressure determination in horizontal boreholes. Even though a water line inevitably occurs in the narrow section of borehole as the result

### Table 3 Parameters of hole sealing

| Code | Dip angle/° | Initial sealing depth/m | Total sealing length/m | Sealing method | Grouting pressure/MPa | W/C | Exposure time/h | Measuring time/h |
|------|-------------|--------------------------|------------------------|----------------|-----------------------|-----|----------------|-----------------|
| \( P_1 \) | 2 | 3 | 21.5 | Reducing-nipple hole + pressurized sealing | 4 | 0.5 | 2 | 552 |
| \( P_2 \) | 6 | 0 | 12.4 | Reducing-nipple hole + pressurized sealing | 4 | 0.5 | 2 | 396 |
| \( P_3 \) | -12 | 3 | 18.6 | Reducing-nipple hole + pressurized sealing | 2 | 0.5 | 2 | 288 |
| \( P_0 \) | 5 | 0 | 22 | Grouting sealing | 2 | 0.8 | 2 | 264 |

![Figure 12](image-url) Build-up curves of gas pressure
of cement hydration reaction, the larger outside section filled with solidified cement could effectively block the gas leakage channel by drilling an eccentric reducing-nipple borehole. Thus, the highest value of 1.52 MPa was properly considered as the original gas pressure of 7# coal seam for a safety purpose.

After grouting cement mortar into borehole, most of the space is sealed. For horizontal borehole, the water line is inevitably formed between the holewall and the sealing medium owing to the cement solidification, which is the main factor causing the failure in gas pressure measurement. Adopting the improvement sealing method by drilling reducing-nipple borehole, the cement in large section can still seal the gas leakage in the small inside section, though cement mortar would shrink in both sections. Thus, the width of gap between hole wall and sealing medium is sharply decreased and the amount of gas leakage is also effectively reduced. During the gas pressure measurement period, a certain grouting pressure is needed to ensure the sealing effect. Only the pressurized cement mortar can seep into and tightly block the fractures around borehole. Whereas, the viscous force and some tiny gravels would impede the mortar seepage at the normal pressure. Additionally, the selection of the initial sealing position is often determined depending on field experience. Sometimes, the initial sealing position starts from the orifice of borehole, which does not avoid the fracture zone. Consequently, the width of the fracture zone should be considered in the hole sealing for gas pressure measurement.

6 | CONCLUSIONS

The previous sealing methods are not applicable for gas pressure measurement in the horizontal cross borehole, owing to the occurrence of water line caused by the autoshrinkage of cement mortar. A series of autogenous shrinkage tests of cement specimens with different water-cement ratios were performed to study the autoshrinkage effect on hole sealing. It is found that the shrinkage amount would decrease with the water-cement ratio rising in the early solidification stage. By the discussion of gas flow in the gap between the sealing medium and holewall, the gas leakage amount in the eccentric model is larger than that of the concentric ring model. Furthermore, the initial sealing position should be kept away from the plastic zone around tunnel, which is related to the lithology of surrounding rock, the buried depth, and the size of tunnel section. Simulation results of the grouting pressure show that the diffusion radius of cement mortar enlarges with an increasing grouting pressure, while the pressure reaching a threshold, the increment of diffusion radius would gradually desert.

According to the above analyses, a pressurized sealing technology by drilling the reducing-nipple borehole was successfully applied for the gas pressure measurement in 7# coal seam, Liulong coal mine. The gas pressure of 7# coal seam of 1.52 MPa is reliable.

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