Experimental and Theoretical Study of the Time-Effect-Based Instability Characteristics of the Gas Drainage Borehole Sealing Section in a Soft Coal Seam

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ABSTRACT: The instability and sealing difficulty confronted by gas drainage boreholes in a soft coal seam weakens the drainage efficiency. To address this problem, the instability characteristics of the sealing section of boreholes are investigated. On the basis of the findings of the mechanical properties of the borehole around the sealing section and in view of the physical and mechanical properties of the soft coal seam, a theoretical analysis was performed. A system consisting of the YYL200 electronic persistent creep test system and the DNS-200 electronic universal tester was used to observe the borehole under different filling conditions. The samples were subjected to a graded loading test, and the Kelvin–Voigt model was selected for parameter inversion and law analysis of the test results. The results show that the collapse of the broken area and the stress concentration and instability of the sealing section after the sealing of the soft coal seam are directly attributable to the instability of the soft coal seam and the sealing difficulty. The mechanical properties of the grouting sealing material are directly related to the loading of the hole-containing sample and dead load displacement. The maximal overall displacement of the sample in group B is close to 1.4 mm. The instantaneous deformation capacity and deformation space reflected by the generalized Kelvin model parameters $E_1$, $E_2$, and $\eta$ are closely related to the mechanical properties of the filling material. The highly stress- and deformation-resistant sealing material can ensure the relative time-effect-based stability within the stress concentration area of the sealing section.

1. INTRODUCTION

Extensive mine gas drainage results indicate that gas predrainage helps to effectively remove the limit exceeding the gas concentration in highly gassy coal mines and from the origin lower and eliminate the gas outburst hazard in the extraction workface.1–3 China possesses many widely distributed coal mines with soft coal seams. The low intensity and poor stability of soft coal seams lead to sealing difficulty in gas drainage boreholes and also directly result in a low gas drainage efficiency and utilization ratio in soft-coal-seam-containing mines.

The first step in gas drainage in a coal seam is to drill boreholes for advancing. Because of its characteristics, soft coal seams encounter interference from complicated environments such as gas fields, stress fields, and mining disturbances. The drainage borehole sealing section is vulnerable to instability and deformation, and thus borehole collapse and blockages appear, as noted in Figure 1. Consequently, following borehole completion, pipes cannot be laid and sealing job cannot be completed on time. Moreover, the grouted borehole sealing section is subjected to stress concentration and gradually becomes unstable and deformed. As a result, coal body fissures around the borehole wall are developed and connect with the coal wall of the roadway, and leaking gas channels are formed. Ultimately, the drainage borehole is poorly sealed and becomes nonfunctional.

In recent years, many domestic and foreign studies have focused on borehole instability after stress concentration. Liang et al. conducted a theoretical analysis of mechanics, established the mechanical model of borehole instability, and performed systematic research on the instability and damage law of the coal body at the depth and wall of the borehole.7 Zhang et al. conducted theoretical solving and numerical simulation on the stability characteristics of a grouted borehole sealing section, and on the basis of fluid–solid coupling theory, they established the mechanical model of the borehole and carried out industrial testing for verification.8 Wang et al. divided the borehole stress into three areas and carried out detailed theoretical mechanics modeling.9 Zhai et al. carried out a theoretical study on the deformation and instability of the borehole in a gassy and outburst-prone soft coal seam and explored the intrinsic reason for the primary and secondary distributions of the stress around the roadway.10,11

However, present studies on the instability of borehole sealing section in soft coal seams remain mostly at the...
qualitative stage. Few experimental studies have been found on the resistance of different grouted sealing materials to borehole instability, and relevant studies considered neither the time-effect-based instability nor the deformation under unchanged borehole stress. As a consequence, the instability of the borehole sealing section in a soft coal seam is not restricted anywhere, and gas drainage there remains nonideal. On the basis of the current study results on the stability of the drainage borehole sealing section and combined with the characteristics of a soft coal seam, the theoretical analysis in this article is focused on the pressure-bearing condition and reasons for the instability in all of the regions of the sealing section in a soft coal seam. Then, by using the creep experiment for the hole-containing sample sealed with different grouting materials, this article studies the creep damage law for the samples under different grouting support conditions. Furthermore, we employed the parameter inversion of the Kelvin–Voigt model. The difference between this study and previous studies is that it uses a physical similarity simulation grouting test and simulated grouting material to carry out a creep stress loading test with inverse test parameters and to quantitatively study the drilling under different conditions. Deformation characteristics and the instability and failure characteristics of the sealing section of the borehole were obtained, and finally a reasonable solution for the easy instability and difficult sealing of the sealing section of the soft coal seam was proposed, which has a certain reference value and practical significance for the efficient gas drainage of the soft coal seam.

2. ANALYSIS OF THE PRESSURE-BEARING CONDITION AND INSTABILITY FACTORS OF THE COAL BODY AROUND THE BOREHOLE SEALING SECTION IN A SOFT COAL SEAM

Following the completion of roadway advancement, the virgin stress equilibrium of rock and the coal seam is broken. In the stress redistribution and equilibrium process, the coal body produces elastic–plastic failure and deformation, and then the stress concentration shifts gradually to the depth of the coal body. After the completion of borehole drilling in a coal seam, along the diameter direction toward the depth of the coal wall within the borehole, a failure zone, plastic zone, elastic zone, and primary rock stress zone appear, similar to the stress distribution around the roadway. Stress zones and pressure bearings are illustrated in Figure 2.

2.1. Analysis of Different Stress Environments in the Perimeter of the Borehole Sealing Section in a Soft Coal Seam.

(1) The stress-lowering zone is also known as the distresses zone, as shown in Figure 2(I). Most of the coal body in the zone has experienced maximal stress. The coal body has undergone deformation and failure to the greatest extent, and only residual intensity is left. The zone falls into the borehole sealing section, which may be called the failure region of the sealing zone. Here, the borehole incurs collapse and deformation that will result in ineffective sealing. In addition, the zone is also where the gas-leaking channels of the borehole sealing section accumulate in large quantities.

(2) Postpeak stress-rising zone, as shown in Figure 2(II). Here, the stress intensity of the coal body has exceeded its maximal compressive strength. Most of the coal body incurs plastic deformation, and its intact and solid structure is damaged; after its development, micro-fissures produce macrofissures that are interconnected. The zone also falls into the borehole sealing section. The stress concentration also easily leads the borehole sealing section here to instability and deformation as time elapses. In the end, the sealing fails.

(3) Prepeak stress-lowering zone, as shown in Figure 2(III). Here, the stress intensity of the coal body has surpassed its maximal compressive strength. Fissures are inevitably developed. Compared with the previous two zones, the coal body around the borehole remains relatively intact.

(4) Primary stress zone, as shown in Figure 2(IV). In the primary stress zone deep in the borehole, little change
occurs to the pressure bearing of the coal body around the borehole, only small quantities of primary fissures exist, and its stability is optimal.

2.2. Reason Analysis of the Failure and Collapse of the Sealing Section in a Soft Coal Seam. In combination with the characteristics of a soft coal seam and according to the stress environment in different stress zones of a coal seam borehole, the reasons for the instability and deformation of the sealing section are analyzed as follows.\(^ {13,14} \)

(1) In the formation of coal, its metamorphic extent directly results in obvious differences in its components and structure. Furthermore, the mechanical properties of the coal body around the drainage borehole directly concern its own stability. Low intensity, easy expansion, easy adsorption, and a small cohesive force also cause the borehole in soft coal seam to be vulnerable to instability.

(2) The soft coal body easily adsorbs water to expand. Hydration leads the coal body to expand and produce a volume deformation, which also directly results in easy instability and deformation of the borehole sealing section in the soft coal seam.

(3) The soft coal seam is armed with a stronger gas adsorption capacity. Most soft coal seam mines are very gassy, and the gas occurring in a soft coal seam is desorbed and released in a great quantity during the borehole drilling process. This release easily causes instability in the stress field and gas field around the borehole, finally leading the relatively broken coal body in the sealing section to deform and collapse.

(4) Relative to other kinds of coal seams, a soft coal seam is more easily affected by ambient conditions such as adjacent seam mining and advancing. Meanwhile, when a borehole is made in a soft coal seam, borehole deviation often occurs, which causes the drilling rod to fiercely disturb the distressed zone at the mouth of the borehole and also directly leads to the easy collapse of the region at the mouth of the borehole after it retreats. It can thus be observed that the stress-lowering zone of the borehole sealing section in a soft coal seam is vulnerable to instability and that deformation and collapse occur easily, causing the pipe not to be laid as a plug after the borehole is completed. The borehole easily deforms following stress concentration in this zone, which helps to promote the generation of gas-leaking channels, and ultimately leads to the failure of borehole sealing. To perform a quantitative study on the time-effect-based instability and failure law of the sealing section, this article employs hole-containing samples to simulate the stress concentration zone of the borehole sealing section and carries out an experimental study.

3. EXPERIMENTAL STUDY OF THE CREEP OF THE HOLE-CONTAINING SAMPLE UNDER GRADED LOADING

3.1. Preparation of Samples for the Experiment. According to the standard recommended by the International Society of Rock Mechanics (ISRM)(DZ/T0261.1-2015), the preparation method and size of the hole-containing samples are determined for this experiment. Square samples (70 mm × 70 mm) are chosen. On the basis of the research findings related to the formulation of the material similar to soft raw coal stated in the literature,\(^ {15,16} \) cement and plaster are mixed with pulverized coal to serve as the aggregate of the material.

Coal samples are drawn from a soft coal seam and crushed and sieved. The sample slurry is configured in a 8:2:10:7 cement/plaster/pulverized raw coal/water mass ratio. After the slurry is evenly mixed, it is poured into the prepared molds. The molds are shown in Figure 3.

After the completion of pouring, the slurry is divided into four groups. Group I is an entire sample. In the center of the three remaining slurries, an 80 mm × 10 mm cylindrical iron rod is placed to simulate a borehole. After standing for 24 days at room temperature, the molds are removed. Then, the samples in four groups are polished on a grinder. Figure 4 and Table 1 show the sample groups and filling materials.

3.2. Experimental Equipment and Principle. A YYL200 electronic long-time creep tester is used for the experiment, as shown in Figure 5.

Graded loading creep is selected for this experiment. This method can effectively avoid the discrete error in experimental results from such external factors as sample preparation and experimental conditions and obtain the loading and dead load displacement under different stress conditions. Prior to the graded loading experiment, a uniaxial compression experiment...

Table 1. Compressive Strength and Details of the Samples in Each group

| Group | Number | Compressive Strength/MPa | Filling Material |
|-------|--------|--------------------------|-----------------|
| A     | 4      | 15.2                     | Intact sample   |
| B     | 5      | 8.9                      | Hole-containing, unfilled |
| C     | 5      | 13.7                     | Hole-containing, filled with sealing materials such as cement |
| D     | 5      | 9.3                      | Hole-containing, filled with sealing materials such as organics |

Figure 3. Sample molds.

Figure 4. Hole-containing samples.

Figure 5. YYL200 electronic long-time creep tester.
is conducted to acquire the uniaxial compression strength of the samples in each group. Experimental results and details are separately shown in Figure 6 and Table 1.

The compressive strength values of the samples in each group are listed in Table 1. By drawing about 80% of these values, four grade-loading stress values are set in total. Once the graded loading creep experiment begins, the tester is operated for first-grade loading. When the loading stress arrives at its preset value, the loading stress is unchanged and the dead load creep experiment proceeds. Then, in turn, four-grade dead loading and the loading creep experiment are conducted. Parameter settings for the experiment are listed in Table 2.

### Table 2. Parameter Settings for the Graded Loading Creep Experiment

| Group | Grade | Axial Load/KN | Stress Level/MPa | Duration of Maintaining Dead Load/min | Loading Duration/min |
|-------|-------|---------------|------------------|---------------------------------------|----------------------|
| A     | I     | 15.069        | 2.871            | 60                                    | 10                   |
| II    | 28.135| 5.742         | 60               | 10                                    |
| III   | 42.203| 8.613         | 60               | 10                                    |
| IV    | 56.272| 11.484        | 60               | 10                                    |
| B     | I     | 8.742         | 1.783            | 60                                    | 10                   |
| II    | 17.474| 3.567         | 60               | 10                                    |
| III   | 26.226| 5.352         | 60               | 10                                    |
| IV    | 34.986| 7.136         | 60               | 10                                    |
| C     | I     | 13.356        | 2.726            | 60                                    | 10                   |
| II    | 26.712| 5.451         | 60               | 10                                    |
| III   | 40.067| 8.177         | 60               | 10                                    |
| IV    | 53.425| 10.902        | 60               | 10                                    |
| D     | I     | 9.114         | 1.861            | 60                                    | 10                   |
| II    | 18.228| 3.720         | 60               | 10                                    |
| III   | 27.342| 5.580         | 60               | 10                                    |
| IV    | 36.456| 7.440         | 60               | 10                                    |

**3.3. Experimental Results and Analysis.** The graded loading creep experiment for the samples in each group is conducted three times, and then data averaging is done so as to reduce the error. The experimental results so obtained are shown in Figure 7.

It can be noted from the curves in Figure 7 that, in the grade-I loading, the samples in all groups have maximal displacement, which can be approximately considered to be the compaction stage in uniaxial compression. After comparison, the displacement (about 0.7 mm) of the samples in group B is knowingly the largest in grade-I loading, suggesting that the samples in this group resist stress loading relatively poorly. An analysis of the overall displacement of the samples in all of the groups in four-grade loading indicates that the overall displacement of the samples in groups A and C is approximate (less than 1 mm), while that in group B is the largest, close to 1.4 mm. This suggests that, compared to the samples in group B, those in group C have a stronger capacity to resist the stress-loading deformation. This also shows that the mechanical properties of the filling material directly affect the capacity of the samples to resist the stress-loading deformation.

It is known from the law as revealed in the four-grade dead load experimental results for the samples that the curves for the first two-grade dead load experiment of all the samples in the four groups are approximately horizontal, namely, the creep displacement is tiny at this time. The variation of creep in the later two-grade dead load experiment is relatively obvious, indicating that the stress-loading level directly affects the dead load displacement of all of the samples. The curves of the hole-containing and unfilled samples and the hole-containing samples filled with organic sealing materials are characterized by an obvious increasing trend. This demonstrates that these samples have a stronger dead load deformation capacity, which reveals that the mechanical properties of filling materials directly affect the time-effect based stability of the samples in the dead load stage.

### 4. STUDY OF THE PARAMETERS OF THE HOLE-CONTAINING SAMPLE CREEP MODEL

**4.1. Selection of the Creep Model.** The study and development of the theoretical creep model are significantly beneficial to the quantitative study of the time-effect-based deformation of the rock and coal body. Parameter inversion of the hole-containing sample creep models can help to directly obtain relevant creep parameter values, quantitatively revealing the time-effect-based deformation law of the samples under loading.

It is observed in Figure 7 that the samples in each group have experienced an elastic strain process in the starting phase of the experiment. After this process, the strain curve rises as time elapses. This verifies that the model not only needs an elastic component but also contains a viscous one. Therefore, the Kelvin–Voigt model is chosen for the parameter inversion in this experiment. The curve of the model is closer to the curve in this experiment. The model consists of a Kelvin component and a spring in series connection, as illustrated in...
In the equations in the model, the capacity of the material to resist instantaneous deformation is directly related to instantaneous elastic modulus $E_1$. The creep deformation amount after ultimate stability is achieved is directly related to extreme creep deformation modulus $E_2$, and viscous flow properties are directly related to viscosity coefficient $\eta$. At the same stress level, the smaller $E_1$ is, the more vulnerable the material is to resisting instantaneous deformation, and the smaller $E_2$ and $\eta$ are, the larger the deformation space of the material is.

$$
\varepsilon(t) = \frac{\sigma}{E_1} + \frac{\sigma}{E_2} \left( 1 - \exp \left( -\frac{E_2}{\eta} \right) \right)
$$  \hspace{1cm} (1)

Matlab (a data processing software) is employed to perform parameter inversion of the experimental results. Taking the experimental results in group B, the fitting curve ($\sigma = 7.136$ MPa) obtained is shown in Figure 9. It can be discovered that the curve of the Kelvin–Voigt model is similar to the fitting curve of the experimental results. The calculation shows that the maximal value of $R^2$ is 0.9963. Moreover, the fitting conclusion from the parameter inversion of the experimental results in the three remaining groups relatively matches with the experimental results. Hence, this model is used to perform parameter inversion to the creep curve of the samples in each group subjected to each graded dead load and quantitatively explore the time-effect-based instability deformation law of the borehole.

4.2. Creep Parameter Inversion. To obtain creep parameters $E_1$, $E_2$, and $\eta$ of the samples in each group in the Kelvin–Voigt model, the experimental results shown in Figure 7 and the least-square method are used to obtain the inverse of the results, as listed in Table 3.

| group | stress level/MPa | model parameter $E_1$/MPa | model parameter $E_2$/MPa | model parameter $\eta$/MPa-h | model parameter $\eta$/MPa-h |
|-------|-----------------|---------------------------|---------------------------|-----------------------------|-----------------------------|
| A     | 2.871           | 5.218                     | 64.47                     | 987.4                       | 987.4                       |
| B     | 1.784           | 3.648                     | 48.01                     | 704.1                       | 704.1                       |
| C     | 2.726           | 4.368                     | 61.29                     | 875                         | 875                         |
| D     | 1.860           | 4.005                     | 55.22                     | 601                         | 601                         |

4.3. Analysis of the Parameter Inversion Results. As shown in Figure 10, it is known after observing the variation law of instantaneous elastic modulus $E_1$ of the samples in all of the groups that, with the increase in the stress level, the model parameter $E_1$ in the four groups shows an approximately linear increasing trend. This indicates that a higher stress level leads to a poorer capacity of the samples of all groups in resisting instantaneous deformation. Among the groups, the samples in group B have the lowest instantaneous elastic modulus $E_1$, while that in group A is the largest. This reflects that, after the borehole drilling is completed in the mine coal seam, the borehole sealing section is vulnerable to instability because the entirety of the rock and coal body is damaged. Meanwhile, on the basis of the $E_1$ value of each group subjected to the same stress level, it can be observed that the mechanical properties of the sealing material are also directly related to the variation of instantaneous elastic modulus $E_1$. The cement grouting material can ideally reduce the instantaneous deformation and
instability capacity of the borehole sealing section. That is, the larger the grouting support strength of the borehole, the greater the stability of the borehole sealing section.

As noted in Figure 11, observing the variation law of the extreme creep deformation modulus $E_2$ of all groups indicates that the stress level increase causes model parameter $E_2$ to show a linear increasing trend. Among them, $E_2$ of groups A and C is closer. This reflects that, after the cement material is filled, the extreme deformation space of the hole-containing samples is very close to that of the intact samples, and the stability is optimal. However, after a grade III stress level is exerted, the $E_2$ value of the samples in groups A and C shows a difference. This suggests that, as subjected to larger stress loading, the cement sealing material has a limited capacity of resisting the borehole deformation. A comparison of the $E_2$ value of all the samples shows that the unfilled and hole-containing samples and the ones filled with organic material have larger extreme deformation space capacities. This can also verify that the grouting support strength is inversely proportional to the deformation space displacement in the perimeter of the sealing section.

As shown in Figure 12, the variation curve of the viscosity coefficient $\eta$ of the samples in all groups indicates that, with the increase in the stress level, the viscosity coefficient $\eta$ also exhibits a nonlinear increasing trend. And the coefficient of the samples in groups A and C is very similar (with respect to the variation law of the curves in Figure 11). This suggests that the hole-containing samples filled with cement material is characterized by a smaller space deformation capacity and stronger stability. Following grade III and grade IV loadings, the difference appears in viscosity coefficient $\eta$, and the hole-containing samples filled with cement material begin to gradually lose stability. Comparing the coefficient in all groups reveals that the mechanical properties of the grouting material are also directly related to the space deformation capacity of the hole-containing samples. This indicates that a larger grouting support strength can decrease the space deformation capacity of the sealing section, making it relatively stable.

It can be known from the above experimental conclusions that the instability process of the borehole sealing section in a soft coal seam is subjected to a strong time effect. Under this time effect, the sealing section instability and deformation is a dynamic process. Hence, highly efficient sealing engineering of the gas drainage borehole in a soft coal seam should not only manage to avoid the deformation and collapse after the borehole is completed but also demand more with respect to the mechanical properties of the grouting material to strengthen and seal the borehole, in particular, the pressure- and deformation-resistant capacity. High-strength pressure- and deformation-resistant sealing material can effectively resist instantaneous deformation of the borehole sealing section due to the stress concentration while effectively lowering the extreme space deformation capacity in the load-bearing process of the sealing section. This helps the gas drainage borehole not to be vulnerable to time-effect-based deformation and instability and finally to prevent gas leakage. Therefore, it radically solves the difficulty faced by the soft coal seam in highly efficient gas drainage. Because of the limitations of research methods and test conditions, this article did not use physically similar simulation methods to carry out related creep tests. Future research should be closer to the actual force on site.

5. RESULTS AND DISCUSSION

(1) Theoretical analysis shows that the collapse of the hole in the broken zone and the stress concentration instability of the sealing section after grouting and sealing directly lead to the easy instability of the drilling in the soft coal seam and the difficulty in sealing.

(2) The total displacement of each group of samples in the loading stage is negatively correlated with the loading strength. The total displacement of the sample with holes and unfilled samples reaches 1.4 mm, and the total displacement of the complete sample and the sample with holes filled with cement materials is less than 1 mm. It shows that the mechanical properties of the grouting sealing material are directly related to the loading of the sample with holes and the displacement of the dead load.

(3) The inversion results of model parameters $E_1$, $E_2$, and $\eta$ show that the porous specimens filled with cement-like materials have a smaller displacement and a higher stability than the unfilled and filled organic materials.

(4) To solve the problem of the poor sealing effect of drilling holes in soft coal seams, a high-strength, high-compression, deformation-resistant material is needed.
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