INTRODUCTION

To keep coal mining constant in deep underground mines, the roadway stability is of significance as it is tightly related to the transportation of coal and safety of coal miners.\(^1\) However, it is a challenging task to ensure the roadway stability over its planned service life in underground coal mines, though many high-strength and high-rigidity support systems have been applied.\(^2-5\) When a roadway is driven through weak rock mass especially in soft coal mass, more attention needs to be paid as the time-dependent deformation of coal mass affects its stability obviously.

Normally, for a deeply buried soft coal roadway, the problem of rheological deformation during excavation and after support installation is rather serious. In extreme conditions, the larger roadway convergence and reduction of the roadway cross section may occur frequently.\(^6-9\) To address this issue, the conventional support techniques such as rock bolting,
U-shaped steel sets, concrete steel sets, and some compound systems have been tried and succeed in some cases.\textsuperscript{10-12} However, the mentioned methods normally emphasized the high-rigidity and high-strength support on surrounding rock mass and neglected the rheological properties of coal mass. Consequently, more support cases, particularly in the weak rock mass with time-dependent behavior, failed over time and therefore further reinforcement or readjusted excavation was needed during its service life, causing high maintenance costs.\textsuperscript{13}

To enhance the stability of roadway in rheological coal mass, grouting techniques were generally adopted as they can improve the quality of coal mass.\textsuperscript{14} After grouting, the coal mass possessed some excellent performances such as higher strength and integrity, lower rheology, and permeability.\textsuperscript{15} Considering these advantages of grouting, some traditional grouting methods (ie, pregrouting and delayed grouting) were applied to roadway reinforcement.\textsuperscript{16-19} However, it should point out that the application of conventional grouting approaches in the coal roadway was limited due to the special circumstance of soft coal mass, that is, poor groutability and small diffusion radius.\textsuperscript{20,21}

To overcome these limitations, a new grouting method for soft coal mass namely Jet Grouting (JG) was presented referring to JG treatment in geotechnical engineering.\textsuperscript{22-25} By the JG method, the high-pressure cement grout was injected into soft coal mass and mixed with coal particles cut by high-velocity jet and therefore a “coalcrete” composite with high strength was generated.\textsuperscript{26} Also, the model was verified. Then, more columns were created around the roadway profile, and therefore a stable coalcrete support structure was produced before roadway excavation. After excavation, other methods such as shotcrete and rock bolts can be further used for reinforcement and then a JG support system was subsequently generated. Roadway convergence can be controlled by JG support, as the resistance to deformation of soft coal mass was improved. Though the JG technique is very encouraging, there was little research on the roadway stability considering rheology of surrounding coal mass as this technique is relatively new. Moreover, to the authors’ knowledge, there were no reports about numerical modeling about JG coalcrete in deeply buried underground roadway. Therefore, it is necessary to comprehensively evaluate stability of rheological roadway after the novel JG treatment and to reveal its mechanism by numerical methods systematically.

This study focuses on the time-dependent deformation of the coal roadway and the presented JG support system. General geology of the project area was introduced, and the time-dependent behavior of coal mass was revealed based on the field measurement. Then, a time-dependent model with CVISC was constructed and simulated in terms of the rheological parameters from back-analysis on field measurements. Furthermore, the model was confirmed. Based on the verified model and parameters, a JG support system was generated in the numerical model for controlling roadway deformation. The results are very promising and can be used for guiding the JG application in practice.

2 GEOLOGICAL SETTINGS AND FIELD MEASUREMENT

2.1 Background of the study area

The studied roadway is located in the working face (shown in Figure 1,2A) at Huaibei coalfield. The coal mass is extremely soft, which normally leads to the collapse at tunneling face (Figure 1,2B). Figure 1,2C shows the original support system in this roadway. However, the practice experience showed that this support scheme cannot resist the larger deformation

FIGURE 1 The study area. (a) The layout of the investigated roadway, (b) the driving conditions in soft coal mass, (c) original support scheme, (d) the field photographs of roadway deformation
of the roadway and most of the support structures failed, as soft coal was easy to be in rheology.

The large convergence of roadway occurred at around 1 ~ 2 months and needed to maintain frequently (Figure 1.2D). Such results further confirmed that the rheology of weak rock mass deteriorated the roadway stability. In addition, the rock mass rating (RMR) and geological strength index (GSI) were used for obtaining the mechanical parameters of rock mass. Then combined with laboratory tests of samples, the rock mass properties are summarized in Table 1.

2.2 In situ measurement of roadway deformation

Roadway deformations were monitored by instrumenta-
tion. The in situ measurement of sidewall convergence is shown in Figure 1. It is clear that the deformation of the roadway exhibited time-dependent behavior. There are two phases (phases A and B) indicating the deformation behavior of the roadway. After roadway excavation, the displacement of the sidewalls increased over time. The maximum convergence of sidewalls displacement reached 880 mm. In practice, this roadway needed to be maintained many times, which means that the roadway cannot keep stable in its service life.

3 NUMERICAL MODELING

3.1 Time-dependent modeling method

The fine difference code FLAC3D was used in this study to perform time-dependent numerical modeling. A 3D numerical model was established (Figure 3). At XZ direction, the established domain is 60 m x 60 m. At YZ direction, the length of the model is 100 m to avoid the boundary effect. The model is fixed at the bottom, and roller boundaries are applied at XZ and YZ directions. Equivalent stresses are applied on the top boundary of the model.

Figure 4 shows the support structure. In this model, the cable and shell structural elements are used for generating rock bolts and shotcrete, respectively. By the equation given in Eq.1, the supporting effect of U-shaped steel sets is transferred to equivalent elastic modules and the sum of elastic modules (U-shaped steel set and shotcrete) can be applied to shell elements in the numerical model. Table 2 shows the mechanical parameters of support structures. Furthermore, the displacement of roadway is recorded by the monitoring points on the roadway profile.

$$E = E_0 + \frac{A_g E_g}{A_c}$$  

(1)

Where $E$ means the elastic modulus of all support materials, $E_0$ is the modulus of shotcrete, $A_g$ means the cross-sectional area of U steel set, $E_g$ denotes the elastic modulus of steel, and $A_c$ is the cross-sectional area of the shotcrete.

In this study, the burger-creep viscoplastic model (CVISC) is used for simulating the time-dependent property of coal according to recommendation. Rheological parameters are critical for analyzing the deformation behavior of coal mass. Thus, the back-analysis method is utilized based on literature. Table 3 shows the results. As for the elastic-plastic parameters of soft coal mass and rock mass, they are given in Table 1.

3.2 Validation of the model

The simulation results were monitored in 300 days and shown in Figure 5. The solid line represents the results from simulation, and the scatters show the field measurements. It
is clear that the simulated results are quite close to monitoring convergence, which means that the established numerical model and its input parameters are reasonable. Based on the model, a series of operations such as the validation of the new support system can be tested.

### 3.3 Establishment of JG support system in the numerical model

The mechanical properties of soft coal mass can be improved by the JG method. In the field, the high-pressure grout with a water-cement ratio of 0.8 was injected into the coal mass, and coal mass was cut and mixed with cement grout with the rotation of the drill. Then, the drill stem withdrew and a coal-grout column was formed subsequently. Based on the tests, the diameter of coalcrete column is around 400 mm. The constructed coalcrete columns can be a stable support structure, which can reduce the roadway deformation effectively. Thus, in this study, a JG support structure was further established to explore the supporting effect on controlling time-dependent deformation in the roadway (Figure 6). It should point out that the stress conditions, boundary domain, support materials, etc. are consistent with the original model.

According to the field and laboratory test results, the diameter of the coalcrete column in this study is set to be 400 mm (shown in Figure 7A) and the mechanical parameters of coalcrete are given in Table 4. The Mohr-Coulomb model is employed to coalcrete. In coalcrete columns, a very fine mesh (around 0.1 m) is used (Figure 7B). Grouting reinforcement in the bottom corner of roadway is applied and shell elements are used for simulating the grouting effect. Similarly, a 300-day creep of coal mass is set in order to examine the coalcrete support system on controlling rheological deformation of the roadway over time.

### 4 Analysis and Discussion of JG Support

#### 4.1 JG support on the horizontal displacement of the roadway

Some key monitoring days are chosen (ie, 1 d, 7 d, 15 d, 150 d, and 300 d) to reveal the evolution of horizontal deformation of the roadway by JG. From Figure 8A, as can be seen, because of the reinforcement, two internal moving areas were formed in the floor (shown by red dotted circle in 1 d). The

| Parameters, unit | Rock bolt | U-shaped shed | Shotcrete |
|------------------|-----------|---------------|-----------|
| Elastic modulus, GPa | 200       | 200           | 30        |
| Poisson’s ratio | 0.3       | 0.25          | 0.15      |
| Diameter/thickness, mm | 22        | 15            | 100       |
| Length, mm       | 2400      | –             | –         |
| Pretensioning, kN | 80        | –             | –         |
horizontal displacement of these areas was not obvious over time, while the extent of the areas gradually expanded (from 7 d to 15 d). On the 15th day, the movement of the two sidewalls became stable. After that, the horizontal displacement did not increase obviously and the values kept relatively stable (from 150 d to 300 d).

The deformation rate of the sidewall convergence over time is shown in Figure 8B. The tendency of roadway deformation exhibits a two-stage behavior. In 15 days, the maximum deformation rate is 11.4 mm/d. In this stage, the roadway showed convergence in a small extent in a short time. After the 15th day, the deformation rate reduced sharply to a constant value that is greater than zero. The results indicated that the jet grouting support scheme can efficiently decrease the rheological deformation of roadway in the horizontal direction, control total horizontal convergence, and reduce the stabilization time.

4.2 | JG support on the vertical displacement of the roadway

After JG support, the evolution of vertical convergence of the roadway is shown in Figure 9A. It is clear that the displacement of the floor was larger than that of the roof after roadway excavation (1 d). Then, the roof and shoulder of roadway had a relatively larger deformation (from 7 d to 15 d). From 150 to 300 days, the vertical deformation was almost unchanging, which means that the JG can control the vertical deformation of roadway effectively.

4.3 | General comparison of control effect between conventional support and JG support

To intuitively display the JG effect on controlling the rheological deformation of the roadway, the comparative results of conventional support and JG support are thoroughly plotted in Figure 10. From the collected statistics data, it can be seen that the JG support system can reduce the convergence of roadway and the deformation rate considerably. Some indicators evaluating the control effect of JG are summarized in Table 5. After the JG support application, the sidewall convergence and roof-to-floor convergence reduced by 64.7%, and 45.6%, respectively. As for the deformation rate of roadway, the values in sidewalls and roof-to-floor decreased by 65.6% and 6.1%. Furthermore, the stabilization time of roadway reduced significantly by JG support, from 60 days to 15 days, a 75% reduction. Overall, the JG support system can control the deformation of soft coal roadway efficiently and restrain the time-dependent behavior of coal mass, indicating that the roadway stability is enhanced drastically.

| TABLE 3 | The rheological parameters of coal mass |
| η_M (MPa.h) | G_M (MPa) | η_K (MPa.h) | G_K (MPa) |
| 3.38e6 | 1.36e2 | 6.09e8 | 2.21e2 |

Figure 9B displays the deformation rate of roof-to-floor convergence. Similar to the development tendency of horizontal displacement, the vertical displacement also exhibited a two-phase deformation property. As can be seen, the maximum deformation rate is about 22 mm/d in 15 days. Compared with the traditional support system, these values were much smaller. Generally, the JG support scheme can reduce the vertical displacement of the roadway, especially on the roof. The time-dependent behavior of roof was restricted notably, indicating the roadway stability was improved after JG treatment.
**FIGURE 7** The details of the JG support system. (a) the size of JG columns, (b) the mesh discretization and monitoring points setting.

**TABLE 4** The mechanical parameters of coalcrete

| Mechanical parameters | Cohesion (MPa) | Friction angle (°) | Elastic modulus (GPa) | Tensile strength (MPa) | Poisson’s ratio |
|-----------------------|---------------|-------------------|-----------------------|-----------------------|----------------|
| Values                | 3.71          | 30.2              | 4.56                  | 2.64                  | 0.24           |

**FIGURE 8** The evolution properties of the roadway by JG in the horizontal direction, (a) the evolution of roadway deformation, (b) the deformation rate of horizontal convergence.

**FIGURE 9** The evolution properties of the roadway by JG in the vertical direction, (a) the evolution of roadway deformation, (b) the deformation rate of horizontal convergence.
5 | CONCLUSIONS

The time-dependent behavior of soft coal roadway was revealed based on field measurement. A numerical model of the rheological roadway by jet grouting treatment was generated. Based on that model, the effect of JG support on controlling the horizontal and vertical deformation of the roadway was further investigated. Besides, a general comparison of conventional support and JG support was performed. The main results of the study are as follows:

1. Based on the project background and in situ measurement, the time-dependent property of soft coal was found and a two-phase rheological feature of the roadway was revealed.
2. According to the field practice, a time-dependent simulation model was validated by comparing the field measurement with the simulated results, showing the model and its corresponding parameters were accurate.
3. A model with JG coalcrete columns (diameter of 400 mm) and other support materials was established based on the validated model and field measurement. The control effect of JG support on roadway deformation was systematically investigated.
4. The horizontal and vertical deformation of the roadway reduced significantly after the JG application. The deformation rate and stabilization time of roadway by JG support decreased considerably compared with conventional support. The work can greatly promote the JG application in underground coal mines.

ACKNOWLEDGMENTS

The work was supported by the projects of the “National Key Research and Development Program (2016YFC0600901),” “National Natural Science Foundation of China (Grant No. 51574224, 51704277).” The authors are grateful to Huaibei Mining (Group) Co. Ltd. Special thanks to Dr Zuqi Wang for her encouragement and help.

CONFLICT OF INTEREST

The authors declare that they have no competing interests.

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How to cite this article: Sun Y, Li G, Zhang J. Investigation on jet grouting support strategy for controlling time-dependent deformation in the roadway. Energy Sci Eng. 2020;8:2151–2158. https://doi.org/10.1002/ese3.654