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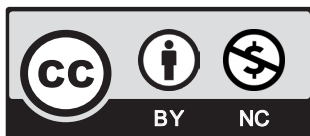
A ROADWAY IN CLOSE DISTANCE TO COAL SEAM IN DEEP MINE: LOCATION SELECTION AND SUPPORTING PRACTICE BASED ON CREEP CHARACTERISTICS OF SURROUNDING ROCKS

In deep mines, since the broken surrounding rocks & high-stress level of a roadway being near a coal seam, the creep characteristics of surrounding rocks should be considered as the main influencing factor in the selection for the roadway's location of the lower coal seam. Both VI15 and VI16-17 coal seams of the Pingdingshan No. 4 Coal Mine, in China, Henan province, are close coal seams with a depth of around 900 m. According to the traditional formula calculation results, when the lower coal seam roadway is staggered 10 m to the upper coal seam goaf, the roadway pressure behaviour is significant, and the support becomes difficult. In this paper, the properties of surrounding rock were tested and the influence of lower coal seam on the stress state of surrounding rock is analysed by numerical simulation, and systematic analysis on the stress and creep characteristics of the surrounding rock of the mining roadway and its effects on the deformation is performed. The results demonstrated that the roadway's locations in the lower coal seam can be initially divided into three zones: the zone with accelerated creep, the transition creep zone and the insignificant creep zone. The authors believed that the roadway layout in an insignificant creep zone can achieve a better supporting effect. Based on the geological conditions of the roadway 23070 of the VI16-17 coal seam of the Pingdingshan No. 4 Coal Mine, combined with the above analysis, a reasonable location of roadway (internal offset of 30 m) was determined using numerical simulation method. The reliability of the research results is verified by field measurement. The above results can provide a reference for selecting the roadway's location under similar conditions.

Keywords: deep mine, close distance, coal seam group, location of roadway, creep

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1. Introduction

Close (ultra-close) coal seams (groups) are extensively distributed around China. Researchers and engineering staff have carried out in-depth systematic theoretical works and engineering practices around a mining layout, stress distribution and the selection of roadway's location and supporting mode, which effectively guarantees safe and efficient mining for coal seam [1-2]. The research results mainly focus on the three following aspects:

- (1) According to the characteristics of rock strata movement and floor's roadway damage of the close-distance coal seam group, researchers proposed a reasonable layout of working faces. Based on the radon's geophysical and chemical properties that it belongs to radioactive substance and inert gas, Zhang [3] proposed a new method for detecting the failure depth of coal seam floor and roof of the close-distance coal seam. Considering the mining condition for the close-distance medium-thick coal seam group (spacing 6.4-18.9 m) of Lijiahao Mine, Zhang [4] determined the floor damage depth using theoretical analysis and geological radar detection. In combination with stress concentration characteristics under coal pillars, a reasonable internal offset of the working face is considered to be 12-14 m. Yang [5] and Yan [6] studied the selection of a reasonable offset in coal seams group mining and suggested that the lateral range of the zone affected by interlayer stress should also be considered in addition to the initial offset. Yong [7] studied the movement deformation and damage characteristics of overburdened rock during upward mining for a close-distance coal seam group. They also suggested that the layout of the working face of the upper coal seam should avoid a tensile-failure zone above the remaining coal pillars of the lower coal seam.
- (2) In the selection for the roadway's location, researchers consider that a roadway arranged in the low-pressure zone is conducive to controlling the roadway's deformation. Li [8] defined ultra-close coal seam using three indices: the maximum thickness of the lower and upper coal seams, floor failure depth during upper coal seam mining and roof's collapse height during mining for lower coal seam. Furthermore, they established a relevant mechanical model and proposed a theory that roadways should be arranged in a low-pressure zone. Yong [7] studied vertical stress distribution in the strata under wide coal pillars of ultra-close coal seam; obtained "saddle shape" distribution law for vertical stress in the coal seam and pointed out that lower roadway should be arranged away from the "saddle shape" zone with increasing stress. Ju [9] used a combined method of geological radar detection along with theoretical calculation to explore the dimension effect of the remaining upper coal pillars of the close-distance coal seam group on the surrounding rock stress of the lower mining roadway. It is considered that the reduction in the coal pillar's dimension and making the pillar completely in the plastic yielding state can reduce stress-affected zone, which can facilitate the control of surrounding rocks of the lower roadway.
- (3) Aiming at solving problems that the surrounding rocks of a mining roadway of a close-distance coal seam can readily fragment and is generally difficult to provide support. Researchers usually controlled roadway's deformation using the joint support method, considering the deformation and failure mechanism of the surrounding rocks. The distribution characteristics of the surrounding rock-bearing structure of roadways were systematically examined using theoretical analysis and numerical simulation under the

condition of dynamic load and creep by Qin [10]. Based on the control effect of different support methods, a reinforcement scheme for deep dynamic soft rock roadway was proposed and applied. Based on the application, the zonal reinforcement scheme of “fix cable to shed, floor pressure relief, deep-shallow composite grouting” is proposed and put into practice. The results can provide theoretical support and reference for the determination of supporting parameters in deep roadways. Majcherczyk et al. [11-13] adopt the methods of theoretical calculations and field practice to study the feasibility of reducing the support density when roadway bolt support cooperates with a steel arch support. The results show that under different mining conditions support system frames can be spread up to 1.5 m apart when using rock bolts between them. He proved that underground monitoring is a good way for roadways to support design validation over a long time period. Sun [14] adopted a numerical simulation method to calculate stress distribution and damage characteristics of the lower roadway in an ultra-close (0.8-2 m) coal seam group. Based on this, a three-dimensional joint roof control technology is proposed, which is based on full-length anchoring using hydraulic-expanded anchor pile and advanced intubation method for the roof. Yu [15] used the theoretical calculation method to study lower stress distribution under coal pillars in close-distance coal seam (with an interlayer spacing of 7.4 m). They proposed that the low-pressure zone in the lower coal seam begins to appear at the position of 22.5-27.5 m of the coal pillars. Moreover, they analysed the length, yow and line spacing of an anchor pile support of the lower mining roadway, in which they finally obtained reasonable support parameters under service conditions.







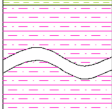







histogram	lithology	thickness/m
	medium sandstone	5
	sandy mudstone	4.5
	V ₈ coal seam	5
	aleuvite	8
	V ₉₋₁₀ coal seam	3.5
	silty mudstone	8
	sandy mudstone	163.5
	aleuvite	4
	sandy mudstone	4.5
	VI ₅ coal seam	3.5
	mudstone	3.2
	sandy mudstone	6.3
	VI ₆₋₁₇ coal seam	3.8
	sandy mudstone	8

Fig. 1. Comprehensive histogram of coal seam

The Pingdingshan No. 4 Coal Mine consists of multiple coal seams such as IV, V, VI, VII, etc. At present, V and VI groups subjected to main mining both belong to close-distance coal seams. From top to bottom, the V coal group is divided into V8 and V9-10 coal seams with an average interlayer spacing of 10 m and an average burial depth of 700 m, respectively. VI group is divided into VI15 and VI16-17 coal seams from top to bottom with an average interlayer spacing of 8 m and an average burial depth of 900 m. The histogram of the coal seam is shown in Figure 1.

According to the traditional calculation results about an internal offset (internal offset is 7 m) (Yan [16]) in the actual production process, the internal error distance in the mining gateway of the lower coal seam of the VI group is set to be 10 m, which satisfies the calculation result of the traditional formula as shown in Figure 2. However, in the actual production process,

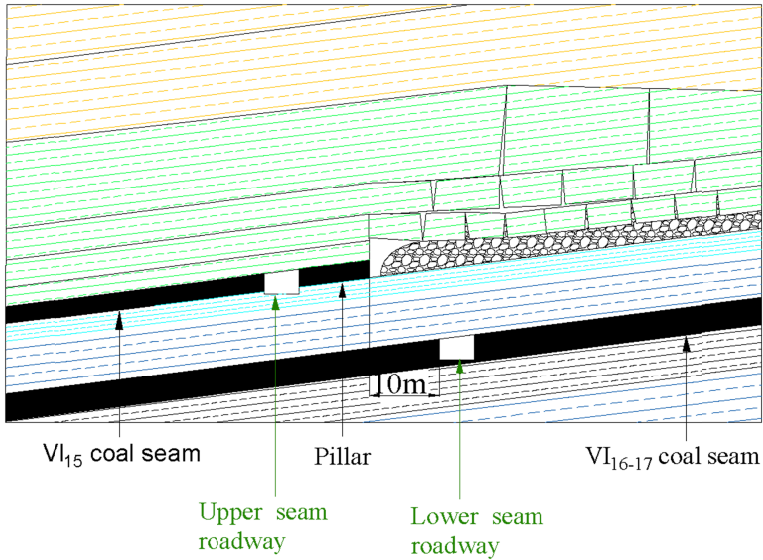


Fig. 2. A schematic diagram of roadway's layout in lower coal seam

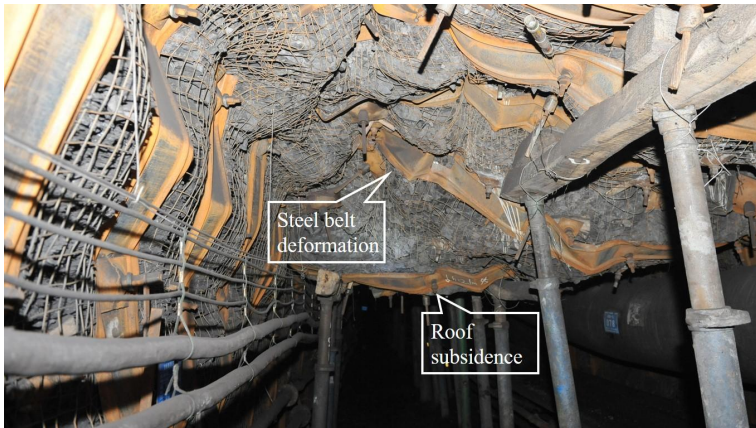


Fig. 3. Severe deformation and failure of roadway

the roadway's pressure is significant, and the deformation damage is severe (Fig. 3), which has adverse impacts on production.

As the VI16-17 coal seam of the Pingdingshan No. 4 Coal Mine has a larger burial depth (average depth is 900 m) and is affected by the support pressure of the upper VI15 coal seam, the fragmentation and creep characteristics of surrounding rocks are significant. This is because of the creep behaviour of the roadway's surrounding rocks. The present paper further explores reasonable locations of the roadway layout and carries out an engineering practice to provide a reference for selecting the roadway's location under similar conditions.

2. Creep characteristics of roadway's surrounding rocks

2.1. Outline of tests

The test samples were taken from the floor of the VI16-17 23130 ventilation roadway of the Pingdingshan No. 4 Coal Mine (the average burial depth is 900 m), and the lithology was sandy mudstone. To reduce the discretisation of the test results caused by the sample's individual difference, the core is taken from the roof of the complete sandy mudstone without cleavage and processed into cylindrical test pieces with a dimension of $\varphi 50 \times 100$ mm. The test pieces are divided into two groups, and each group consists of 7 test pieces (six are used for determining the conventional mechanical parameters, and one is used for the creep test).

Before the creep test, the physical and mechanical parameters of the sandy mudstone were tested in accordance with the requirements in the "Test Procedure for Physical and Mechanical Properties of Coal and Rock". The physical and mechanical parameters include colour, bulk density, compressive strength σ_c , tensile strength σ_t , elastic modulus E , Poisson's ratio μ , cohesion c , internal friction angle φ and the uniaxial and triaxial compressive strengths, etc. The specific values are shown in Table 1.

TABLE 1

Physical and mechanical properties of sandy mudstone

Color	Bulk density/kg/m ³	σ_c /MPa	σ_t /MPa	σ_{3c} /MPa
Linen gray	2.47	9.8	3.4	18.4
E /GPa	μ	c /MPa	φ /(°)	
13.46	0.396	5.63	38.6	

2.2. Test on creep characteristics of surrounding rocks

The three samples of sandy mudstone are marked as M1, M2 and M3, the rock specimens are tested by step loading. According to the data of the coal mine, the lateral pressure coefficient is 1, the creep characteristics of sandy mudstone with burial depth of 300 m, 600 m and 900 m were studied. At this time, the confining pressure is 7.5 MPa, 15 MPa and 22.5 MPa. The triaxial compressive strength of sandy mudstone is about 18.4 MPa when the confining pressure is 10 MPa, and the loading step is 3 Mpa. During the test, the confining pressure was applied to the set value at the loading rate of 1 MPa / min to keep the confining pressure constant, then the deviator stress is applied to the set value at the loading rate of 3 MPa / min, and the deviator stress is maintained until the deformation of the specimen is stable or destroyed. The specific scheme is shown in Table 2.

TABLE 2

Triaxial creep test scheme

Sample number	Size ($\varphi \times h$) (mm)	Confining pressure (MPa)	Deviator stress (MPa)		Loading time (h)
			Initial load	Step	
M1	49.7×100.7	7.5	0	3	12
M2	49.9×100.3	15	0	3	12
M3	49.8×100.6	22.5	0	3	12

The triaxial creep test results of sandy mudstone under different confining pressures are shown in Figure 4.

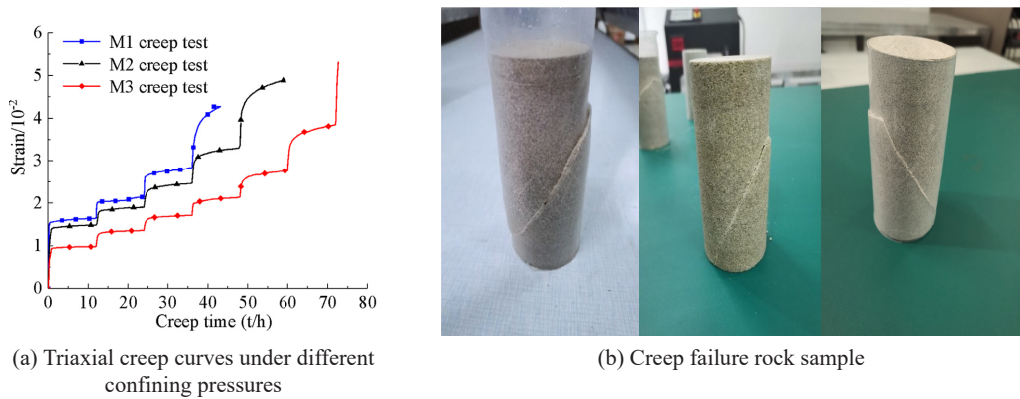


Fig. 4. Creep test results of samples

As can be seen from Figure 4:

- (1) At the initial stage, the strain of the specimen increases rapidly, and then it maintains stable creep at the deviatoric stress level; when the deviatoric stress is at least 12 MPa when the confining pressure is 7.5 MPa, the accelerated creep occurs;
- (2) At the same deviator stress level, the strain decreases with the increase of confining pressure. In the first three loading stages, the average strain of 22.5 MPa is 47.0% lower than that of 15 MPa and 59.5% lower than that of 7.5 MPa.
- (3) The greater the confining pressure is, the greater the stress level. When the confining pressure is 7.5 MPa, the specimen is damaged when the stress level is 12 MPa; when the confining pressure is 15 MPa, the specimen is damaged when the stress level is 15 MPa; when the confining pressure is 22.5 MPa, the specimen is damaged when the stress level is 21 MPa.

3. Selection of reasonable location of mining roadway for lower coal seam

3.1. Considering roadway's deformation characteristics under the creep of surrounding rocks

Based on the triaxial creep test results of sandy mudstone, different creep models [17,18] are selected for parameter identification and comparative analysis of creep curves of rock samples, and the constitutive model which can accurately describe the creep characteristics of sandy mudstone is selected. The nonlinear visco-elastic-plastic model of six elements proposed by Paraschiv-Munteanu [19] is the best way to describe the creep results. The model is shown in Figure 5, and the analysis process is as follows:

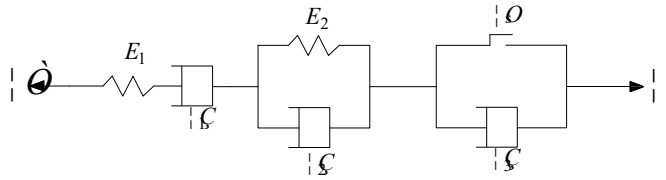


Fig. 5. Nonlinear visco-elastic-plastic model of six elements

The constitutive equation is as follows:

$$\varepsilon = \begin{cases} \frac{\sigma}{E_1} + \frac{\sigma}{\eta_1} t + \frac{\sigma}{E_2} \left[1 - \exp\left(-\frac{E_2}{\eta_2} t\right) \right], & (\sigma \leq \sigma_s) \\ \frac{\sigma}{E_1} + \frac{\sigma}{\eta_1} t + \frac{\sigma}{E_2} \left[1 - \exp\left(-\frac{E_2}{\eta_2} t\right) \right] + \frac{b}{\eta_3} \left[\exp\left(\frac{\sigma - \sigma_s}{b} t\right) - 1 \right], & (\sigma > \sigma_s) \end{cases} \quad (1)$$

Where b is the material constant, MPa·h; η_1 is the initial viscosity coefficient of the initial material.

When fitting the parameters of the constitutive model, the loading stage without accelerated creep and the stage with accelerated creep are selected respectively. As the buried depth of the target roadway is about 900 m and the confining pressure is about 22.5 MPa, the experimental data of confining pressure of 22.5 MPa, deviatoric stress of 15 MPa and 21 MPa are used to fit the parameters of the constitutive model. By using the improved Boltzmann superposition principle [20], the step loading curve is transformed into a separate loading curve. The test results are shown in Figure 6.

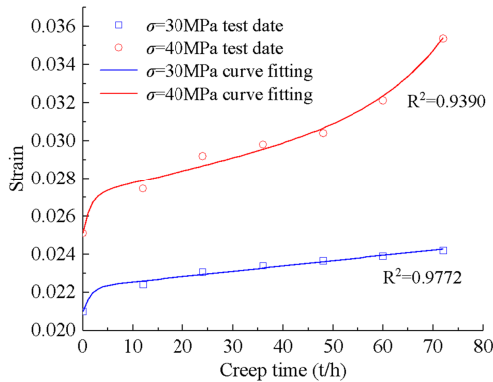


Fig. 6. Fitting curve of nonlinear visco-elastic-plastic model of six elements

The fitting curve equations of $\sigma = 15$ MPa and $\sigma = 21$ MPa are as follows:

$$\varepsilon(t) = \frac{\sigma}{0.715} + \frac{\sigma}{11.914} \left[1 - \exp(-0.646t) \right] + 1.401 \times 10^{-5}, \quad R^2 = 0.9772 \quad (2)$$

$$\varepsilon(t) = \frac{\sigma}{0.837} + \frac{\sigma}{356.416}t + \frac{\sigma}{10.289} [1 - \exp(-0.656t)] + 6.076 \times 10^{-5} \times \left[\exp\left(\frac{\sigma - \sigma_s}{0.083}t\right) - 1 \right], \quad R^2 = 0.9390 \quad (3)$$

When the confining pressure is 22.5 MPa and the deviatoric stress is 15 MPa, the sandy mudstone has no accelerated creep, and the $R^2 = 0.9772$, the creep parameters of sandy mudstone are as follows: $E_1 = 0.715$ GPa, $E_2 = 11.914$ GPa, $\eta_1 = 18.443$ GPa/h. When confining pressure is 22.5 MPa and deviatoric stress is 21 MPa, accelerated creep occurs in sandy mudstone, and $R^2 = 0.9390$, the creep parameters of sandy mudstone are as follows: $E_1 = 0.0.837$ GPa, $E_2 = 10.289$ GPa, $\eta_1 = 356.416$ GPa/h, $\eta_2 = 15.684$ GPa/h, $\eta_3 = 1.366$ GPa/h.

3.2. Numerical simulation on the reasonable locations of roadway

Numerical simulation analysis on the selection of roadway's location was carried out using FLAC 3D software. To comprehensively reflect different spacing and roadway's offset, the model selects coal rock mass at the junction of 23110 working face and VI15-23090 and the adjacent area with a dimension of $210 \times 100 \times 52$ m. The mesh size of the coal seam is 0.5 m, and another mesh size is determined depending on the distance of the investigated area from the junction. The total number of units is 57,260; the model and mesh partitioning are shown in Fig. 7. The model's custom development was carried out according to the actual conditions of the Pingdingshan No. 4 Coal Mine.

According to the uniaxial creep test results, a nonlinear creep model (Eq. 1) that can fully reflect the attenuation creep, stable creep and accelerated creep is adopted. The model is defined as the Mcvisc model. Based on the principle of the least squares method, the parameters of the creep model are determined using numerical software Origin (Table 2). The interface for secondary development reserved by the FLAC 3D program is used to develop the custom model program.

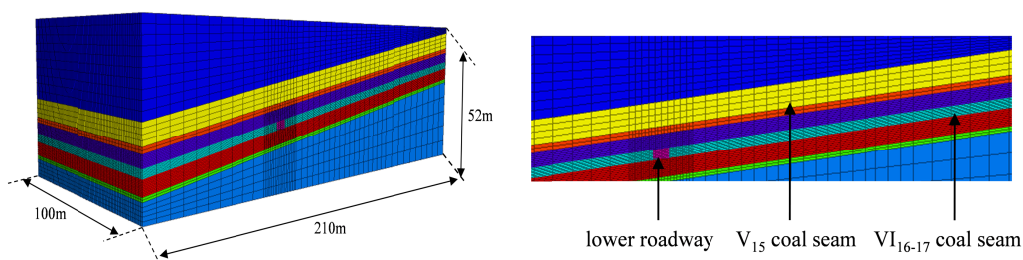


Fig. 7. Integrated model used in numerical calculation

The interlayer spacing between VI15 and VI16-17 coal seams of the Pingdingshan No. 4 Coal Mine is 3-12 m. To determine a suitable roadway location, deformation and stress of surrounding rock are simulated for the roadways with different interlayer spacing (3-12 m) and internal dislocation distance (5-35 m) under the mining effect. A total of 35 computation models are obtained, and the simulation scheme is shown in Table 3. The points are arranged on two

sides e.g. roadway’s roof and floor surfaces are used to measure displacements; the points are arranged every 3m in the VI16-17 coal seam to monitor/measure vertical stress of coal seam after completing the mining on the VI15 coal seam.

TABLE 3

Simulation scheme

Interlayer spacing / m	3, 5, 8, 10, 12
Internal dislocation distance / m	5, 10, 15, 20, 25, 30, 35

Stress distributions in the roof and floor of the protective roadway under different internal dislocation distances are shown in Figure 8. When the dislocation distance is 10 m, the stress of surrounding rock is greater than 25 MPa for the interlayer spacing of 3 m and 5 m. However, when the dislocation distance is 20 m, the stress of surrounding rock is greater than 25 MPa for the interlayer spacing of 3 m, which is higher than the maximum stress to initiate accelerated creep of the surrounding rocks. When the dislocation distance is 30 m, the stress of the surrounding rock is lower than the original rock stress regardless of interlayer spacing. Therefore, the roadway layout of close distance coal seams and the influence of creep should be considered according to the traditional formula.

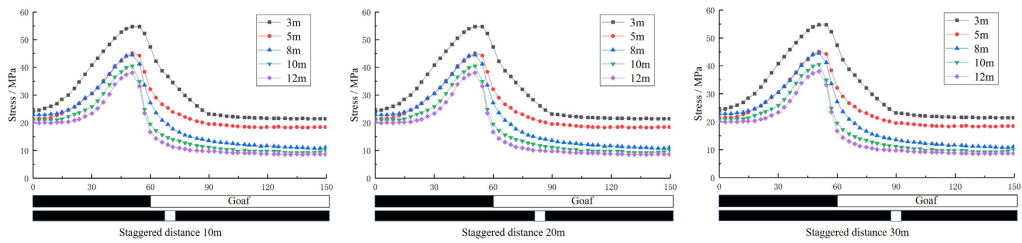


Fig. 8. Stress distribution in the roadway’s surrounding rocks

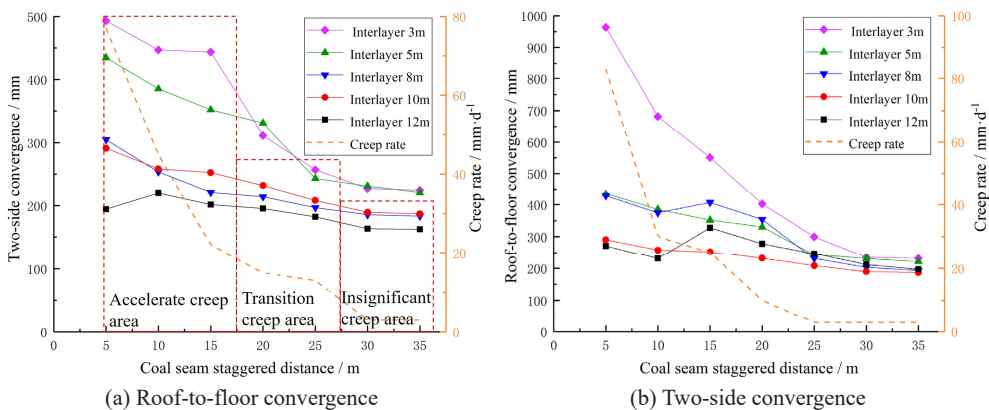


Fig. 9. The relationship between deformation, deformation rate and internal staggered distance of roadway’s surrounding rocks

It is clear that within the range of 0-15 m, the two-side and roof-to-floor convergences of the roadway change dramatically, reaching 45 mm/d and 150 mm/d respectively (Fig. 9). Moreover, the accelerated creep is more obvious when the interlayer between roadway layers is 3 m and 5 m. The range of 15-30 m corresponds to a transition zone having a creep rate from fast to slow, where the moving speed of the roadway surface is slow. The range of 15-30 m is the area of creep rate from fast to slow, and the deformation rate of roadway becomes slow, which is the creep transition area; the range of 30-35 m is the area of low creep rate, which is the insignificant creep area. Therefore, the lower protection roadway should be placed in the area where the creep is not obvious, that is, selecting 30 m as a reasonable staggered distance can effectively reduce the stress of surrounding rock and slow down the deformation of the roadway.

4. Industrial Tests

4.1. Selection of supporting mode

Both VI15 and VI16-17 coal seams of the Pingdingshan No. 4 Coal Mine belong to ultra-close coal seams, and the interlayer spacing changes greatly. After the upper coal seam is mined, the stress states of different locations on the roof's floor are quite different. Therefore, the change in interlayer spacing should be fully considered in the design of the roadway's support.

According to Figure 10, the roadway is greatly affected by the creep deformation of the surrounding rocks when the interlayer spacing is less than 5 m. Therefore, 5 m was used as a boundary line to carry out the partitioned protection for the roadway with different interlayer spacing. Concerning the mine's experience, the integrated support scheme with the anchor-mesh-belt as the basic support and the anchor cable was chosen as the reinforcing method. The roadway is divided into three conditions for support (Fig. 11), and the specific supporting scheme is shown in Table 4.

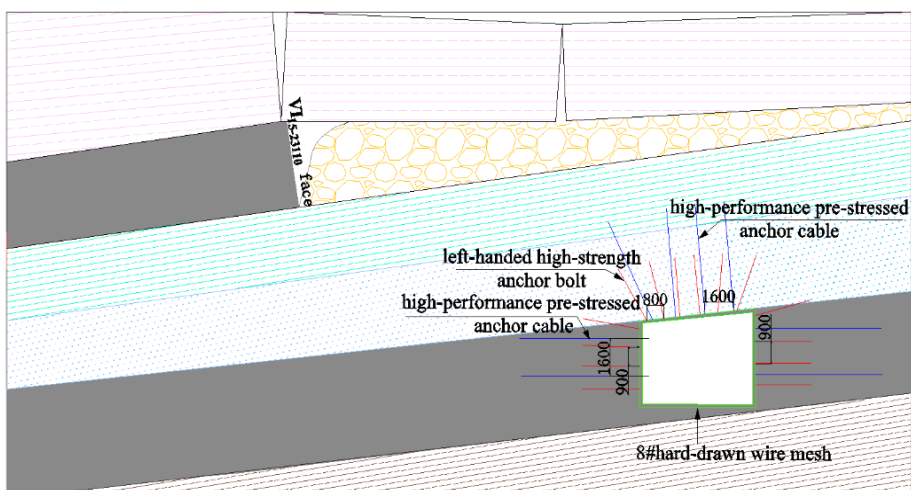


Fig. 10. Schematic diagram of support method for lower mining roadway

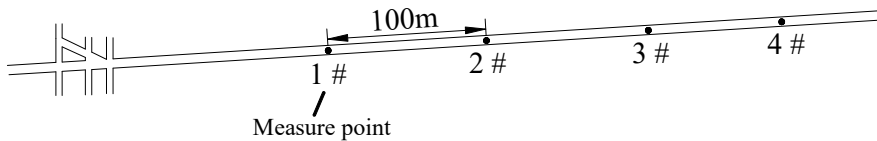
TABLE 4

Partitioned support scheme

Interlayer spacing of coal seam		Basic support	Reinforcing format
<5 m	under substantial coal	Bolt + mesh + belt	Short anchor cable
	under goaf	Bolt + mesh + belt	
>5 m		Bolt + mesh + belt	Short anchor cable

4.2. Detection of the surface displacement of roadway

According to the previous description, the staggering distance between the lower roadway and the coal pillar left in the V15-23130 working face is set to 30 m. Four surface displacement measuring stations are arranged with the cross point method to measure the height and width of the lower protection roadway. The location of the measuring station and the effect of roadway support at different measuring points are shown in Figure 11a. The change of roadway surface area is shown in Figure 11b.

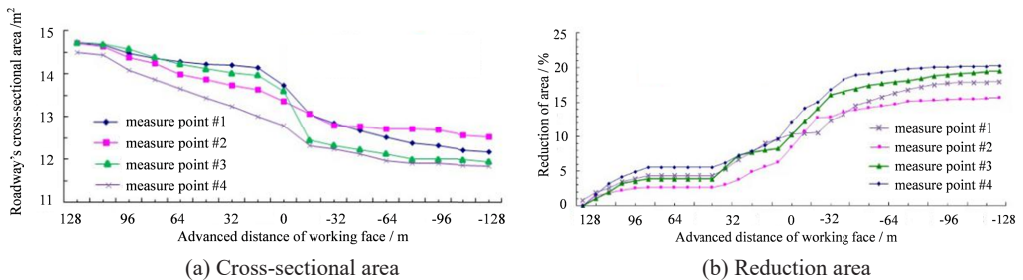


(a) Location of the measuring station



(b) Effect of roadway support

Fig. 11. Measure point layout and supporting effect



(a) Cross-sectional area

(b) Reduction area

Fig. 12. Variation curves for the cross-sectional and reduction of area of the lower roadway

It is clear that the deformation of the roadway's surrounding rocks tends to be stable when the working face is advanced for 128 m (Fig. 12). The cross-sectional areas of the lower protective roadways at the four measuring points are 12.18 m², 12.53 m², 11.95 m² and 11.84 m², respectively. The original cross-sectional area is 14.84 m², so the reduction of area is 17.92%, 15.57%, 19.47% and 20.22%, respectively. The maximum reduction of area is 20.22%, and the average value is 18.30%. The supporting effect for the tested roadway is shown in Figure 11b.

It can be seen from the reduction of roadway area that when the roadway stagger distance is 30 m, the shrinkage and change rate of roadway area are insignificant.

5. Conclusions

- (1) The characteristics of the mining roadway of the VI16-17 coal seam of the Pingdingshan No. 4 Coal Mine include large burial depth, high ground pressure and low surrounding rock strength. It is proposed that the creep characteristics of surrounding rock should be considered in the selection of the reasonable position of mining roadway in the lower seam of close distance coal seam mining. The areas showing accelerated creep of the surrounding rocks should be avoided as much as possible.
- (2) The stress and deformation characteristics of roadway's surrounding rocks under different interlayer spacing and different dislocation distances are studied theoretically and numerically. The results show that the surrounding rocks under 30 m staggered distance are within the areas with insignificant creep, which verifies that the proposed selection method for roadway's location considering the creep characteristics of surrounding rocks is reasonable.
- (3) A partitioned dynamic supporting method is proposed based on the above reasonable staggering distance. Based on the interlayer spacing as the discrimination criterion, the adopted support method of bolt + mesh + steel belt is obtained/selected when the interlayer spacing is less than 5 m. When the interlayer spacing is larger than 5 m, the short anchor cable is adopted for reinforcing and supporting. Through the verification by on-site engineering practice, the average reduction of roadway's area is 18.30%, the deformation of roadway is small, and the convergence rate is stable.

Acknowledgments

We acknowledge the financial support for this work, provided by Supported by National Key R&D Program of China (2018YFC0604705), the National Nature Science Foundation of China (No. 51874282).

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