Analysis on stress characteristics of floor in thick seam working face at initial stage of fully mechanized top coal caving mining

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Abstract: Coal seam working face mining will cause the redistribution of the stress field in the mining floor, which results in the deformation and damage of the coal and rock mass. The stress on the open-off cut floor of the working face at the initial stage of fully mechanized top coal mining of coal seam is different from other positions. Knowing the change of the stress characteristics of the rock formation in this area is significant for the safe mining of the coal seam. To investigate the characteristics of the stress changes in the rock formation in the open-off cut floor of the working face at the initial stage of fully mechanized top coal mining of thick coal seam, a distributed fiber-optic strain testing technology was used for dynamic monitoring of the stress distribution in the rock formation in the open-off cut floor of the working face, based on the working face of a mine in Huainan, China. The results showed that the change in fiber-optic strain distribution throughout the monitoring period corresponded well with the lithology of the formation. The fiber-optic strain in the ⑥ mudstone, ⑦ limestone, and ⑧ fine sandstone in the control area of the drilled fiber optic cable was subject to compressive strain, indicating that the floor of the working face was subject to overall compression due to the influence of the mining action. The fault structure limited the extent and magnitude of the effects of mining stresses laterally in the rock formation. The overall fiber-optic strain in the ④ sandy mudstone and ⑤ fine sandstone located on the outside of the open-off cut floor of the working face did not change significantly. The lagged impact distance of the mining stress was 35 m.

1. Introduction
As a universal engineering disaster, the floor damage induced by coal seam mining has a complex correlation with mining pressure, that is, the floor mining deformation and mining pressure behavior is a complex dynamic process of time and space [1]. The floor mining damage causes not only easy deformation of the floor heave but also easy sagging of the support due to the drastic reduction of its bearing strength, increasing the difficulty of moving the support. Besides, under the condition of the floor with (water) pressure mining, the floor mining damage reduces the thickness of the water barrier of the coal seam floor, which reduces the water blocking capacity of the floor, thus increasing the danger of the floor filled with water. Therefore, the correct understanding of the floor mining
deformation and damage law and the mechanical mechanism is of important theoretical significance and practical application value.

In-situ detection of the deformation law and damage depth of the coal seam mining floor is an important technical means to study this problem. Especially for the strong impact ground pressure mine and floor pressure mine, the measured data of floor mining deformation and damage is an important basis for floor deformation protection and formulation of water control countermeasures. At present, there are many methods to detect the damage depth of coal seam floor mining, mainly including the hydrogeological borehole observation method [2], borehole water injection test method [3], shock wave CT method [4], resistivity method [5,6], and distributed fiber-optic technology [7,8]. Dynamic observation of the deformation, displacement, and damage characteristics of the rock formation in the floor through in-situ measurements has greatly improved the accuracy of the judgment of the deformation and damage characteristics of the rock formation on the floor. However, the selected in-situ measured location of the floor in most of the field working face is mostly within the control range of the working face, while there is less research on the stress distribution characteristics of the floor rock mass near the location of the open-off cut of the working face and the stability impact of the mining process on the lower tunnel.

In this thesis, under the actual situation of fully mechanized top coal mining of the working face of a mine in Huainan, China, a monitoring hole was drilled in the floor tunnel to the open-off cut position of the working face, and a distributed strain sensing fiber-optic cable was used to monitor the stress characteristics of the rock formation at different depths under the floor, to determine the stability of the tunnel under the influence of mining pressure and the influence range of the stress below the open-off cut of the working face.

2. Principle of distributed strain fiber-optic testing technology
The distributed strain fiber-optic testing technology described in this thesis is a spontaneous Brillouin optic time domain reflectometer (BOTDR). The testing host emitted and received Brillouin scattered light from a single end. The peak power of the Brillouin scattered light shifted when the stress conditions at the location of the fiber-optic changed. The linear relationship between the axial strain of the fiber-optic and the Brillouin frequency shift under certain conditions can be used to calculate the strain distribution of the measured object [9]. The results of the rock structure deformation testing may be obtained by implanting a fiber-optic into the rock. As the fiber-optic itself was relatively thin, special processing of the fiber-optic structure was required in the field construction to enhance its adaptability in the deep complex geological environment, to maintain a good coupling with the surrounding rock, while strengthening the fiber-optic cable to meet the engineering monitoring needs.

3 Working face conditions and monitoring scheme design

3.1. Engineering geological conditions
The study area is located in a mine in the Huainan mine area of China, with an elevation of the working face of -430 to -490 m, and an average depth of the working face of about 470 m. The mineable face is approximately 1345 m in strike length and 155 m in slope length. The main mining occurred in the 3# coal seam which has an average thickness of 5.5 m and an actual mining thickness of about 5 m, an average inclination angle of 10°. Both 3# and 1# coal seams are gas outburst seams. In the early stage, gas pre-extracting was carried out for 3# and 1# coal seams at the same time through the corresponding gas extraction equipment and system installed in the floor tunnel excavated below the working face. The working face of 3# coal seam was mined only after the extracted gas met the standards. During initial mining and discharging, roof management was enhanced. During stoping, gas management and tunnel ventilation were strengthened to prevent gas over-limit caused by gas stored in the sandstone layer. The floor lithology of 3# coal seam and other relevant information are listed in Table 1.

The floor tunnel is located in ⑧ fine sandstone and ⑨ sandy mudstone, with the width × height =
4600×3500 mm, and dense and hard limestone on the top and bottom of its rock formation. The support scheme of the 11123 floor tunnel is in the form of "anchor bolt + anchor net + local anchor cable and slurry spraying", and some sections of the fragmented or weak surrounding rocks have been properly reinforced in advance.

3.2. Monitoring scheme design

To effectively obtain the law and difference in stress deformation and damage to the rock mass in the open-off cut floor of the working face during the coal seam mining, a monitoring borehole is designed in the floor tunnel below the open-off cut position of the working face. The monitoring borehole is 26.31 m away from the open-off cut position of the working face. The plane layout of the working face is shown in Figure 2, and the borehole design and corresponding stratigraphic condition profile within the monitoring intersection are shown in Figure 3.
4. Field testing and analysis

4.1. Data collection
The field monitoring started from 26.31 m from the monitoring borehole in the working face and ended at -80.29 m from the monitoring borehole in the working face. It completely captured the strain distribution data of the rock mass before, during, and after mining for 37 times each. The quality of the field data collected was good.

4.2. Fiber-optic strain data analysis
Due to the large number of data sets collected, only 16 of them were selected for processing into graphs and analysis. Figure 4 shows the one-dimensional strain curve, and Figure 5 shows the relationship between strain distribution and strata.

According to the design of the monitoring borehole, the distributed strain fiber-optic cable installed in the borehole can simultaneously measure the stress and damage of the rock stratum within the control area below the working face to be mined and on both sides. The control height of the fiber-optic cable in the monitoring borehole is 0-16.88 m from the hole opening to the top of the hole, with the cable in the control height of 0-8.83 m located directly below the working face to be mined (cable length in the range of 0-26.7 m), and the cable in the control height of 8.83-16.88 m located outside the working face to be mined (cable length in the range of 26.7-57.75 m).

When the working face was mined from the open-off cut position until it moved far away from the monitoring section, the whole rock mass with a fiber-optic length of 0-37 m was subject to compressive strain conditions. The compressive strain was greatest at the interface between ⑥ mudstone and ⑤ fine sandstone at about -1500 με, and the final compressive strain has also reached -1400 με at the interface between ⑥ mudstone and ⑦ limestone, with the compressive strain at other locations remaining on average at about -600 με. However, the rock mass with a fiber-optic length of 10-13 m was subject to tensile strain, with a maximum value up to about 1700 με at the initial stage of mining in the working face. As the working face was advanced, the tensile strain gradually decreased and the position of the peak strain was continuously shifted. The rock mass with a fiber-optic length of 11-13 m was subject to compressive strain from the previous tensile strain, with a final compressive strain of -950 με. The rock mass with a fiber-optic length of 37-57.75 m, on the other hand, was less affected by mining, with a maximum tensile strain of about 300 με only at the stratigraphic separation interface (Figures 4 and 5). At the same time, it can be found that the strain distribution variation of the fiber-optic has a good correspondence with the lithology of the formation.
To more visually analyze the dynamic process of fiber-optic data changes during the monitoring period, the data was mapped in three dimensions, and the results are shown in Figure 6.

Since the sensing fiber-optic cable was located near the open-off cut of the working face, the working face caused fiber-optic sensing in the borehole at the early stage of mining. In particular, the changes were more obvious in the floor rock mass directly below the working face. The internal tensile strain in the \( \text{⑦ limestone} \) and \( \text{⑧ fine sandstone} \) increased when the working surface was advanced at a distance of 18.9 m from the monitoring borehole, and the maximum internal tensile strain in the \( \text{⑦ limestone} \) reached \( +1700 \mu \varepsilon \), while the \( \text{⑥ mudstone} \) was subject to overall compressive strain, with a peak value of about \(-1500 \mu \varepsilon \). This indicated that the coal seam mining broke the stress equilibrium in the surrounding rocks and that the coal pillars at the open-off cut position of the working face were under continuous increasing pressure from the overlying rocks. The pressure was further transferred to the underlying rock mass, resulting in the overall compression of the \( \text{⑥ mudstone} \) layer, which has a relatively low modulus of elasticity, creating compression cracks to some extent. The floor tunnel was affected by the working face mining to some extent, in the form of convergent deformation. However, the floor tunnel was also strongly supported by anchors and other supporting elements to maintain stability. It should be noted that the tail end of the anchor bolts was located in the \( \text{⑦ limestone} \) layer, which led to the concentration of interaction forces in the \( \text{⑦ limestone} \) layer with relatively high modulus of elasticity, resulting in tensile strain and the development of tensile cracks in the limestone. However, due to the high modulus of elasticity of the limestone, and by the anchoring of anchors and other strong supporting structure, the bearing capacity did not exceed the limit, and the rock mass did not have significant deformation and damage. The sensing cables in the \( \text{④ sandy mudstone} \) and \( \text{⑤ fine sandstone} \) were located on the outside of the mining face and were subject to fault structure so that the pressure of the working face coal pillar on the floor at this time could not be effectively transferred to this area.

The fiber-optic strain data fluctuated slightly from 18.9 to 4.6 m as the working face was retracted.
from the monitoring borehole. It was believed that in this process, with the increase of the worked-out area, the direct top rock layer suffered from multiple damages and collapses, and the dynamic changes of stress release, concentration, and release in the working face surrounding rock resulted in small fluctuations in the stresses sustained by the working face floor rock mass. The strain in the ⑥ mudstone, ⑦ limestone, and ⑧ fine sandstone beneath the working surface decreased significantly, especially the tensile strain in the ⑦ limestone layer dropped suddenly from the peak of +1700 με to +450 με, indicating that the stress release phenomenon such as collapse and unloading of a large area occurred in the old top and other force-holding rock layers of the working surface top, thus significantly reducing the pressure on the floor rock mass, and closing part of the fissure.

As the mining position of the working face moved away from the monitoring area, i.e., from 4.6 to -4.6 m, the whole rock mass at the floor of the worked-out area showed compressive strain, while the ④ sandy mudstone and ⑤ fine sandstone layers outside the worked-out area were not affected by mining. During the process from -4.6 m to -35 m, with the increase of the worked-out area, the lateral stress distribution range of the working face surrounding rocks under the influence of dynamic pressure was further expanded, and the tensile strain at the interface between ④ sandy mudstone and ⑤ fine sandstone on the outside of the worked-out area reached +200 με and finally stabilized at about +400 με. It showed that in this process, the rock formations with differences in the modulus of elasticity were affected by the lateral shear stress during the mining of the working face. However, the fault structure significantly limited and reduced the extent and propagation time of the working face mining stress on the rock formation at this location. During the process from -35 to -80.29 m, there was no change in the fiber-optic strain data, which indicated that the rock mass in the monitoring section was not affected by the working face mining and remained in the final stable state. Further, it was determined that the lagged impact distance of the mining stress was 35 m.

Figure 6. Three-dimensional strain distribution diagram.

5. Conclusion

1) Throughout the monitoring period, the strain distribution of the fiber-optic showed a good correspondence with the lithology of the formation. The deformation of the rock formation showed certain stratification and the deformation occurred preferentially in the soft and weak rock formation and at the interface between soft and hard rock formations, indicating that the stratigraphic structure was one of the important influencing factors for the damage of the floor rock formation.

2) The fiber-optic strain in the ⑥ mudstone, ⑦ limestone, and ⑧ fine sandstone in the control area of the drilled fiber-optic cable was subject to compressive strain, indicating that the floor of the working face was subject to overall compression due to the influence of the mining action. The fault structure limited the extent and magnitude of the effects of mining stresses laterally in the rock formation. The overall fiber-optic strain in the ④ sandy mudstone and ⑤ fine sandstone located on the outside of the open-off cut floor of the working face did not change significantly, indicating that the floor rock mass at
this location was less affected by the working face mining action and has good structural stability.

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