Research Article

Experimental Study on the Application of BOTDA in the Overlying Strata Deformation Monitoring Induced by Coal Mining

Jing Chai^{1,2} and Wengang Du¹

¹College of Energy Engineering, Xi'an University of Science and Technology, Xi'an 710054, China

²Xi'an University of Science and Technology, Ministry of Education of the Western Mining and Mine Disaster Prevention and Control of Key Laboratory, Xi'an 710054, China

Correspondence should be addressed to Wengang Du; 403870017@qq.com

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The coal mine working face overlying strata is often disturbed by multiple mining, leading to adverse effects on the working face's safe production and ground surface movement. In the three-dimensional physical model test with the size of $3000 \times 2000 \times 2000$ mm, after the overburden gets stable when the first working face had been extracted, by using three vertical distributed optical fibers based on the BOTDA principle, the deformation law of the overburden caused by the contiguous coal face mining is studied. Results show that, before the working face advanced to 840 mm (near the fiber), the stress law of the overburden was as follows: the middle of the model was under pressure state and the remaining part was under tension state, and the key stratum produced stress concentration phenomena caused by the secondary mining; when the face advanced to 840 mm (through the fiber), the frequency shift curve of the key stratum and the strata on it combined, and the stress concentration in the key stratum disappeared, indicating that the bearing structure of the key stratum gets unstable; compared with the previous monitoring data, when the working face far away from the fiber, the information reflected by the frequency shift data gradually gets single when the working face is far away from the fiber compared with the previous measurement data. The overburden deformation increased dramatically after the key stratum gets unstable. The surrounding rock and fiber will detach when the stratum goes through large deformation such as abscission layer, fracture, and collapse, and the frequency shift monitored by BOTDA cannot characterize the rock deformation in this situation. The experimental method and the results of this paper serve as useful reference for the application of BOTDA technology in geotechnical engineering.

1. Introduction

The coal mine working face overlying strata is often disturbed by multiple mining, such as compound mining, slice mining, and adjacent face mining; the movement law of overburden gets complex due to multiple mining disturbance. The overburden is finally in a steady state after undergoing the processes of fracture and collapse. The multiple mining disturbance may intensify the damage degree of the roof and lead to adverse effects on coal mine safe production and ground surface movement.

Many scholars have done a lot of researches about multiple mining disturbances. Lu [1] evaluated the mining ability of the old coal mine, which can provide reference for the

reuse of residual coal by fully mechanized mining technology; Feng et al. [2] took the residual mining area as the background and put forward the feasibility theory and judgment formula; Gong took the Shaanxi Coal Group Sheng-Hua Coal 3101 mining face as the project background, and the similarity simulation was used to study the characteristics of the roof crack and the pressure distribution in the face; He et al. [3] studied the roof caving of a roadway in Xing-An coal mine and gained the instability mechanism and prevention measures; and Fang et al. [4] studied on the E12505 working face frequent roof caving phenomenon in Cuijiazhai mine and gained the instability mechanism and protective measures. At present, researches on multiple disturbance are mainly focused on roadway support technology,

the feasibility of compound mining, and so on; nevertheless, the research on the again deformation of the overburden after multiple disturbance of coal mining is a rare sight. The deformation and movement of overburden caused by mining activity are a typical “gray structure” problem; the physical similar material model test is one of the main research methods to study the law of strata movement and mine pressure [5]. In the traditional physical model test, single-point pattern sensors such as dial indicator, total station, strain gauge, and pressure gauge are often used to monitor the deformation; they can only gain the external deformation information of the surrounding rock, but to achieve multiscale distributed monitoring within the model is difficult, and there are a large number of sensors and data transmission lines. They will affect the material property and reduce the scientific nature of the experiment. The internal deformation monitoring is still a technical difficulty in a physical similar model experiment.

In recent years, fiber optic sensing technology has made a major breakthrough; it can provide a new way for structural deformation monitoring. Compared with traditional resistive or vibrating-wire strain sensors, optic fiber sensors have the advantages of antielectromagnetic, anticorrosion, and high sensitivity, and layout patterns can be distributed. If the sensor is installed in the tunnel, pile foundation, dam, and other linear structures, like the human nervous system as the perception of structural deformation, it can achieve remote real-time monitoring of the structure [6]. BOTDA has been widely applied to civil and industry infrastructure monitoring [7–9]. In 1990, Mendez et al. firstly applied fiber optic sensing technology to concrete structure health monitoring [10]. In order to improve BOTDA performance such as sensing distance and spatial resolution, many research works have been done. Especially, optical pulse coding and distributed first-order and second-order Raman amplification technology have made it possible to extend the sensing range beyond 100 km with a short spatial resolution [11, 12]. At the end of the last century, domestic scholar Liu firstly introduced the optic fiber sensing technology to the field of domestic geotechnical engineering [13]; Chai et al. [14, 15] used FBG technology to monitor the shaft deformation caused by quaternary unconsolidated layer settlement and verified the reliability of the FBG technique. Optical fiber sensing technology used in the field of geotechnical engineering research and engineering site has broad prospects.

2. Working Principle of BOTDA

The Brillouin optical time-domain analysis technique (BOTDA) was proposed by T. Horiguchi and M. Tateda in 1989 [16]. Compared with the BOTDA system, PPP-BOTDA (pulse pre-pump Brillouin optical time domain analysis) employs the pump pulse with leakage light to achieve a higher spatial resolution. In order to gain a higher spatial resolution, the usual way is to reduce the pulse beam width. However, as the excitation of phonon takes 28 ns, shortening the pulse width will lead to the decrease in Brillouin gain and the deterioration of spectral morphology. The PPP-BOTDA technique excites phonons by changing

the shape of the pump light and adding a pre-pumped pulse wave before the measured pulse light is emitted. With this method, a 1 cm sampling interval and 5 cm spatial resolution can be obtained simultaneously [17].

Based on the Brillouin scattering principle, the continuous detection optical signal and pump pulse optical signal were injected from the two ends of the fiber, when the frequency difference between the continuous light and pulse light is equal to the Brillouin frequency shift in a region of the fiber; the region will produce a stimulated Brillouin amplification effect. The frequency of the two lasers is continuously adjusted. The relationship between temperature, strain, and Brillouin frequency shift is shown in the following equation:

$$\begin{aligned}\delta_{vB} &= C_{v\epsilon}\delta\epsilon + C_{vT}\delta T, \\ \frac{\delta_{PB}}{P_B} &= C_{P\epsilon}\delta\epsilon + C_{PT}\delta T,\end{aligned}\quad (1)$$

where δ_{vB} is the change of Brillouin frequency shift, δ_{PB} is the relative change of Brillouin power, $\delta\epsilon$ and δT are the strain and temperature change, $C_{v\epsilon}$ and C_{vT} are the strain coefficient and temperature coefficient, and $C_{P\epsilon}$ and C_{PT} are the Brillouin power strain coefficient and Brillouin power temperature coefficient. The BOTDA system architecture is shown in Figure 1 [18]. The strain and temperature information of the optical fiber is obtained by detecting the frequency shift variation of the Brillouin signal and the normalized signal power variation value to achieve distributed testing.

3. Model Test Design

3.1. Text General Situation. The model test is based on the geological survey of the overlying strata in a working face of the Qianqiu Coal Mine. The total thickness of the coal seam and its overburden is 805.32 m. A conglomerate is developed at 209.5 m above the coal seam, and the total thickness of the conglomerate is 410.2 m, its tensile strength is 5.5 MPa, and the average compressive strength is 75 MPa, which belongs to the typical hard rock. The geometric similarity ratio is 1:400, the model size is 3000 × 2000 × 2000 mm, the thickness of the simulated floor is 200 mm, the thickness of the overburden is 1740 mm, and the thickness of coal seam is 60 mm. The physical and mechanical parameters of the main coal strata are shown in Table 1.

The physical model is not simulated to the ground surface, the remaining rock mass load is loaded with sandbags, and the material dosage is: 19.9 t sand, 1.0 t gypsum, and 1.7 t lime. The real picture of the physical model is shown in Figure 2.

The boundary coal pillar with the width of 600 mm is left on both sides of the model. The working face is 2400 mm in length and 800 mm in width, and two working faces are excavated. The excavation step is 40 mm. The excavation of the working face is simulated by extraction of galvanized steel pipe. The mining method is shown in Figure 3.

3.2. Monitoring System. Three vertical fibers were embedded in the overlying strata of face 1 in the laying process. The

FIGURE 1: The system architecture of BOTDA.

TABLE 1: Physical and mechanical parameters of coal and rock.

Lithology	Bulk (t/m ³)	Com (MPa)	Tens (MPa)	Elas (10 ³ MPa)
Coal	0.95	16	0.6	3.5
Mudstone	1.97	50	1.2	5
Siltstone	1.7	45	4	28
Conglomerate	1.83	75	5.5	32
Fine sandstone	1.67	30	4	35

FIGURE 2: Three-dimensional model.

identifiers of the vertical fibers are V_{11} , V_{12} , and V_{13} , respectively, and the optical fiber sensor layout pattern is shown in Figure 4. The red number is V_{11} , green for V_{12} , and black for V_{13} ; they are located above working face 1. The instrument type is NBX-6055, the spatial resolution is 5 cm, and the sampling interval is 1 cm.

The frequency shift value of the distributed fiber is the response of the sensor fiber to the external change. When the sensor fiber is embedded in the overburden, the different degrees of overburden deformation and collapse will cause different frequency shift variation.

4. Results and Analysis

4.1. Optical Fiber Test Data. Figure 5 shows the optical fiber V_{11} 's frequency shift data when working face 2 was mining. The abscissa is the Brillouin frequency shift, and the ordinate is the model height. Figures 5(a)~5(f) are, respectively, working face 2 advancing to 0, 480, 680, 840, 1440, and 2400 mm.

The initial state of the optical fiber V_{11} changes in frequency shift to 0 MHz (Figure 5(a)). The frequency shift curve presents a 3-segment distribution when face 2 advanced to 480 mm, the frequency shift of part 1 and part 3 are positive, and part 2 is negative (Figure 5(b)). Compared with advancing to 360 mm, the curve adds 3 peaks in the lower part of the model when advancing to 480 mm, and there is a peak in the conglomerate location. The height of the caving zone is about 0~500 mm after face 1 mining, the peak of part 1 is in the face 1 caving zone range, and face 2 mining caused the broken rock in the caving zone to move again. The frequency shift curve when advancing to 680 mm is shown in Figure 5(c); same as before, the fiber is still under compression in the middle part and under tension at both ends, and the frequency shift fluctuation gets severe compared with advancing to 480 mm, indicating that the degree of influence caused by Re mining has increased as the face continues to advance. The frequency shift curve when advancing to 840 mm is shown in Figure 5(d); the curve has a large change compared with previous ones. The curve became a 2-part distribution from being a 3-part distribution; the frequency shift is negative in the range of 700~1740 mm and is positive in the range of 0~700 mm, the curve gets smooth gradually, and no peak phenomenon appears. The frequency shift curve when advancing to 1440 mm is shown in Figure 5(e). Most of the frequency shift value is negative; it is positive only in the lower part of the model range from 400 to 800 mm. The frequency shift curve when advancing to 2400 mm is shown in Figure 5(f), and the whole face 2 excavation is over at this time. After face 2 is far away from the optic fiber, the frequency shift is mainly negative, and the absolute value increases gradually with face 2 advancing forward.

It can be seen that the contact relationship changed between the fiber and the surrounding rock from V_{11} 's frequency shift. The stress state of the fiber gets complex from being simple gradually, which indicates that the fiber is gradually detaching with the surrounding rock; it cannot characterize the stress state of the surrounding rock in this situation. The surrounding rock of face 1 is in a stable state before face 2 mining; then, the balance of the surrounding rock stress state was broken after face 2 mining, and the stress of the surrounding rock is redistributed. Before face 2 advanced to 840 mm, the stress law of overburden is as follows: the middle part is under pressure and both the ends are under tension, the secondary mining caused the key stratum stress concentrating, and the mutation of the frequency shift indicates that the nearby strata are in a violent activity. When face 2 advanced to 840 mm, the frequency shift curve of the key stratum and the strata on it combined and the stress concentration in the key stratum disappeared, indicating that the bearing structure of the key stratum gets unstable.

4.2. Contrastive Analysis of Two Working Face Data

4.2.1. Working Face near the Fiber. Figure 6 shows the frequency shift curve of the two working faces in the process near the fiber. Comparing the absolute value, the frequency shift peak is 300 MHz when face 1 mined to 560 mm and is

FIGURE 3: Mining style of the working face.

(a) Vertical fiber layout real picture

(b) Vertical fiber spatial location

FIGURE 4: Optical fiber sensor layout pattern.

90 MHz when face 2 mined to 560 mm; it is much lower than face 1 mining. Because face 2 is far away from the optic fiber, the elastic deformation energy impact induced by mining has a large consumption when transferring to fiber V_{11} . Moreover, the overlying stratum above the working face 1 has been destroyed, rock storage potential elastic energy has been fully released, and face 2 mining will affect the overlying strata movement of face 1, but the impact is much smaller than the mining face below it. When the working face 1 is close to V_{11} , the fiber is in the pressure state in the range of 0~500 mm. The closer the working face is to the fiber, the larger the frequency shift is; the change of the frequency shift is caused by the advance abutment pressure in front of

working face 1; when working face 2 is close to V_{11} , the frequency shift is the 3-part distribution, the middle part is under pressure, and the remaining was under tension; the secondary mining caused the key stratum stress to be concentrated.

4.2.2. Working Face through the Fiber. Figure 7 shows the frequency shift curve of the two working faces in the process through the fiber. As shown in Figure 7(a), when face 2 is through the optical fiber, the frequency shift curve is the 2-part distribution, the frequency shift of part 1 is positive, the fiber is in tension state, and the frequency shift of part 2 is negative indicating that the fiber is in a compression state.

FIGURE 5: The optic fiber frequency shift of face 2 mining.

FIGURE 6: Optic fiber V_{11} 's frequency shift of face 2 and face 1 when near the fiber.

FIGURE 7: Optic fiber V_{11} 's frequency shift of face 2 and face 1 when through the fiber.

When working face 2 passed through the fiber, the accumulation elasticity energy of the key layer in the conglomerate layer had released, and the key stratum loses its support function due to the secondary disturbance, while the overburden on it is in the pressure state together. As shown in Figure 7(b), when working face 1 passed through the optical fiber V_{11} , the fiber is in tension state in the range of 0~1200 mm, and there is no obvious frequency shift change in the range of 1200~1740 mm. The frequency shift peak is +500 MHz, the frequency shift decreases as the model height increases gradually, and the range of surrounding rock deformation reached a height to 1200 mm position. The working face is advanced to the position of the fiber, and the rock formation in the fiber position is broken, but the deformation of the strata is different, which leads to the difference change of the frequency shift. Because the optical fiber and the surrounding rock are in close contact, when the strata is moving downwards, the optical fiber is in tension state by the friction

of the surrounding rock, and the tensile stress decreases gradually with the increase in the model height. At this time, the fiber is located in the collapse area.

4.2.3. Working Face Away from the Fiber. Figure 8 shows the frequency shift curve of the two working faces in the process away from the fiber. Figure 8(a) is face 2 away from the optical fiber; the measured data is the frequency shift value for the working face advanced from the 960 to 2400 mm region. As shown in the figure, most of the optical fiber is in the compression state, with the middle of the fiber in a state of tension.

According to the characteristic of the curve, the frequency shift is maximum in the height of the coal seam position, which is the core position of the caving zone, and the compressive stress is the largest. With the increase in the height, the absolute value of the frequency shift is gradually reduced, and most of the frequency shift is 0 MHz in the

FIGURE 8: Optic fiber V_{11} 's frequency shift of face 2 and face 1 when away the fiber.

height of 500 mm, where the optical fiber is in the external stress balance. The 500~850 mm range of the fiber is in the state of tension; the frequency shift monotonically decreases in the height range of 1200~1740 mm and finally returns to zero at the top of the model. The frequency shift curve shows a "hump" shape. Compared with the working face 1 mining process, as shown in Figure 8(b), working face 1 mining has obvious "step shape" changes, which can distinguish the different deformation degree of the surrounding rock.

4.3. Analysis of the Overlying Stratum Structure. Figure 9 shows the structure of the overburden based on optic fiber monitoring. There is no isolated coal pillar in the middle of the two working faces, and the key stratum is in the same group. The overburden moving range is small when face 1 mining, and the longitudinal fissure perforation forms the masonry structures. According to the real model photos and the monitoring data of the optical fiber, the range of the caving zone is about 0~500 mm, and it is not extended to the key stratum of the conglomerate layer. The key stratum is in the fissure zone. The working face 2 is located inside the model and cannot directly observe the deformation condition. Therefore, it can only deduce the law of overlying rock movement through the distributed fiber monitoring results. From the analysis of results in "Optical Fiber Test Data", the key stratum structural damage occurred when working face 2 advanced to 840 mm. Fractured rock blocks produced a rotation in a positive direction due to the support of the cantilever beam in the coal wall side, and the rock blocks of the key stratum above the face 1 caving zone produced a reverse rotation; both the rock blocks tilted toward the middle of the caving zone and produced an articulation. After the loss of the key layer support, the overlying strata above the

working face further compacted in the mined-out area, leading to the compressive stress increasing the lower part of the fiber. Working face 2 mining results in a significant increase in ground surface subsidence on top of the model; according to the measured data, the amount of subsidence increased from 4.8 to 6.5 cm.

5. Experimental Discussions

5.1. The Reliability of the Test. The distributed sensing fiber can be used to test the deformation of the surrounding rock in the physical model test and judge the working face pressure. But the coupling between the model material and the sensing fiber is worth exploring.

BOTDA optic fiber sensing technology to detect the deformation of the material or structure is to paste the sensor fiber or embed it in the structure by detecting the axial strain of the fiber itself to achieve structural deformation distributed monitoring. The contact relationship between the optical fiber and the material is a major factor affecting the monitoring results.

According to the results of analyses in Optical Fiber Test Data, compared with the previous monitoring data, the fiber response information gets single after face 2 advanced to 840 mm, and the frequency shift curves do not have peak characteristics, and the curve is gradually gentle. The deformation of overburden increased dramatically after the instability of the key stratum, the surrounding rock and fiber will detach when the stratum produces an abscission layer and collapse, and the strain monitored by the optic fiber cannot characterize the stratum's deformation. Increasing the coupling between the model material and the sensing fiber is an effective way to solve the above problem.

FIGURE 9: The picture of the model's overlying strata structure.

5.2. Ways to Improve. The test fiber is a 2 mm single-mode optical fiber. The optical fiber is prefixed to the specific position of the model frame and prepulled, and then laying similar materials on a layer-by-layer basis; no binder is used between the material and the optical fiber. Therefore, it is unavoidable that the rock is separated from the sensor fiber after a large deformation occurs.

It is now considered to solve the coupling problem from the performance, structure, and external binder of the fiber matrix material. The following is an example: choose the materials where the elastic modulus is similar to the model material to improve the optical fiber and the measured material strain transfer relationship; change the cylindrical

packaging for the belt packaging or spiral packaging, or paste the small disc at a certain distance on the fiber; and choose adhesive materials with good compatibility with model materials and coating on the surface of the fiber. Such methods require further experiments to verify their effectiveness.

6. Conclusions

In this paper, by analyzing the distributed optical fiber arranged in the three-dimensional physical model, the overburden deformation of adjacent coal face mining is studied, and the following conclusions are drawn:

- (1) After the adjacent working face was mined, the secondary disturbance broke the stress balance of the surrounding rock and the stress distribution of the surrounding rock redistributed. Before the working face advanced to 840 mm (near the fiber), the stress law of overburden was as follows: the middle of the model is under pressure and the remaining is under tension, with the secondary mining causing the key stratum stress concentration
- (2) When the face advanced to 840 mm (through the fiber), the frequency shift curves of the key stratum and the strata on it combined, the frequency shift curves do not have peak characteristics, and the stress concentration in the stratum disappeared, indicating that the bearing structure of the key stratum gets unstable
- (3) Compared with the previous monitoring data, when the working face is far away from the fiber, the information reacted by the frequency shift gets single, the overburden's deformation increased after the key stratum gets instable, and the surrounding rock and fiber will detach when the stratum produces an abscission layer and collapses, yet the strain monitored by the optic fiber cannot characterize the strata's deformation

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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