Research on the key technology of distributed fiber monitoring in tunnel bottom drum

Chai Jing¹,², Wang Zixv¹, Lei Wulin¹, Du Wengang¹, Zhang Dingding¹,²

1 School of Energy and Mining Engineering, Xi’an University of Science and Technology, Xi’an 710054, China
2 Key Laboratory of Western Mine Exploitation and Hazard Prevention, Ministry of Education, Xi’an 710054, China

Abstract: The bottom drum of the roadway is one of the common dynamic pressure phenomena in the process of coal mine production, which can easily affect the material transportation and personnel walking of the coal mine, even destroy the roadway when it is serious, which restricts the safety and efficiency of coal mine production. To improve the backward monitoring method of the tunnel bottom drum deformation, a method of monitoring the bottom drum of the roadway based on distributed fiber monitoring technology is proposed. Through theoretical analysis, the relationship between the distributed fiber deformation and the tunnel bottom drum is proposed. To verify the accuracy of the formula, a similar model is built. Distributed optical fiber is arranged in the model, and the speckle measurement points are arranged on the surface of the model. The method of DIC distributed fiber monitoring is used to verify. The monitoring results show that the formula proposed in this paper can effectively monitor the displacement change of rock strata. At the same time, the coupling between optical fiber and rock determines the accuracy of the measurement results. The better the coupling between optical fiber and rock, the more accurate the measurement results are.

Key words: Roadway; Monitoring of bottom drum; Distributed fiber sensing; Similarity simulation

1. Introduction

Floor heave is one of the common geological disasters in the process of coal mining. Floor heave leads to the reduction of roadway section. After floor heave occurs, pedestrian, ventilation, transportation, and drainage in the roadway will be seriously affected [1-3]. To study the mechanism of roadway floor heave, scholars have done a lot of research on roadway floor heave. Gong et al. [4] measuring stations were arranged on the road to record the conversion deformation during the advancement of the working face. Zhang et al. [5] analyzed the causes of floor heave in soft rock roadway and proposed a roadway floor...
support technology. Through monitoring the deformation of surrounding rock, the feasibility of support technology was verified. At present, the most common method of floor heave monitoring is the cross point method, as well as the differential resistance type, steel-string type, resistance strain gauge type, and inductive sensor. These sensors are all point types, the measuring range is limited, and they can observe the changes of surrounding rock on the roadway surface, so they can not measure the deformation and failure of the deep roadway floor. To more accurately understand the deformation of roadway floor heave, it is necessary to use a new measurement method.

Optical fiber sensing technology is a new type of sensing technology, which uses light as a carrier and optical fiber as a medium to sense and transmit external signals (measured objects). The distributed optical fiber sensor can continuously measure the external physical parameters along the optical fiber geometric path. Because of its physical characteristics, optical fiber sensor has great advantages, such as lightweight, small volume, strong anti-electromagnetic interference ability, radiation resistance, good electrical insulation performance, good flexibility, wide measurement frequency band, real-time monitoring, high sensitivity and resolution, distributed monitoring and so on. Optical fiber sensing is more and more widely used in geotechnical monitoring[6]. Wang et al. Used distributed optical fiber sensing technology to monitor the deformation of tunnel shield[7-8]. Zhang[9] used the distributed optical fiber sensing technology to monitor the ground settlement and obtained the vertical deformation profile imaging within the monitoring range. Zhang Hecheng et al. Successfully used distributed optical fiber sensing technology in the coal mine, implanted optical fiber into coal seam roof and floor, and monitored roof and floor deformation in the coal mining process[10-11].

Physical similarity model test is one of the main research methods in mining engineering. The use of these methods effectively promotes the development of overburden deformation theory and has important guiding significance for coal mining. The physical model test is based on the similarity theory. Under the condition of basic similarity, the engineering problem is simplified into a laboratory model according to a certain similarity ratio. The relevant parameters of the model test can be obtained by various monitoring methods, and then the obtained rules can be pushed back to the prototype. Chai et al[12-13] also used distributed optical fiber in an indoor similar model.

In this paper, distributed optical fiber sensing technology will be used to monitor the deformation of roadway floor heave in the process of coal mining. The research results can verify the feasibility and effectiveness of distributed optical fiber in monitoring the deformation of roadway floor heave.

2. Distributed optical fiber principle
Because of its physical structure characteristics, optical fiber is only sensitive to axial deformation, The position of optical fiber in rock stratum intersects with the deformation direction of rock stratum, and the deformation of rock stratum will cause the deformation of optical fiber in the corresponding position. Therefore, when using BOTDA to monitor rock mass, the relationship between the monitored optical fiber frequency shift deformation and rock mass deformation can be established.

Firstly, the frequency shift changes monitored by distributed optical fiber demodulators are transformed into the strain changes of optical fibers. The relationship between frequency shift change and fiber strain can be expressed by the following formula:

$$\Delta \varepsilon = \frac{\Delta \nu_B - C_1 \Delta T}{C_2}$$

Where, \(\nu_B\) is Brillouin frequency shift, MHz; \(C_1\) is temperature sensitivity coefficient, MHz/°C;
$C_2$ is strain sensitivity coefficient, MHz/με; $\Delta T$ is temperature variation, °C; $\Delta \varepsilon$ is optical fiber strain. Based on the principle of light scattering, the frequency variation of Brillouin scattering light is measured.

Generally, the influence of temperature change on Brillouin frequency shift can be ignored, so the above formula can be simplified as:

$$\Delta \varepsilon = \frac{\Delta \nu}{C_2}$$

(2)

It can be seen from the above formula that the fiber strain is related to Brillouin frequency shift and strain sensitivity coefficient.

3. Test verification

Based on the above analysis, to obtain the sensitivity coefficient of the optical fiber, the fiber is pulled out in the laboratory, and the two ends of the optical fiber are fixed on the clamps of the fiber puller respectively, the moving distance is controlled by the mobile station to realize the axial stretching of the optical fiber, and the Brillouin frequency shift value under the axial stretching condition is collected by using the distributed optical fiber demodulator. By increasing the distance of the mobile station step by step, a series of Brillouin shift values can be recorded. Then, the strain sensitivity coefficient of optical fiber is obtained by fitting the theoretical strain and Brillouin frequency shift of optical fiber after tension by a least square method.

In the calibration experiment, NZS-DSS-CCO7 strain sensing optical fiber is used, and a polyurethane sheath is arranged outside the cladding of the optical fiber. A distributed optical fiber strain demodulator host NBX-6055A and a control system.

3.1 Experimental scheme

Measure an optical fiber with sufficient length with a tape measure, mark a length of 300mm on the optical fiber, and then fix the optical fiber at the marked position on the clamp of the optical fiber puller. To enable the optical fiber to be clamped by the clamp without being damaged by the clamp, a layer of rubber cushion layer is pasted on the contact surface of two aluminum plates of each clamp, as shown in Figure 2, and then it is pressurized by an air pump, and the pressure generated by the air pump is enough to make the optical fiber have greater friction with the rubber cushion layer and prevent it from slipping.

Use the optical fiber welding machine to weld the optical fiber with the jumper with FC-APC joint, Before welding, put the heat-shrinkable tube into the optical fiber, After welding, you can use the heat-shrinkable tube to protect the welded joint of the optical fiber, Finally, use the laser pen to check whether the optical path is unobstructed, and connect the jumper with the optical nano-meter.
Figure 1. laboratory test device

Start the distributed optical fiber demodulator and optical fiber puller, and carry out the loading test according to the displacement control, the optical fiber is stretched by 0.4mm every time it is loaded until the displacement increases to the optical fiber strain limit. After each load is completed and the load is stabilized for 5 minutes, the Brillouin frequency shift of the optical fiber is collected by using the distributed optical fiber demodulator.

3.2 Test results and analysis

According to the measured Brillouin frequency shift value and theoretical strain under each level of tensile load, the Brillouin frequency shift value of two kinds of optical fibers under different strains can be obtained, as shown in Figure. According to the results given in Figure, the relationship between Brillouin frequency shift and strain of different optical fibers can be obtained by using a linear fitting method, as shown in Figure.

Figure 3. Brillouin frequency shift detected by BOTDA and Comparison of strain monitoring by different sensors.

The fitting relationship between Brillouin frequency shift and strain is \( y = 0.049x - 39.61 \), \( R^2 = 0.999 \).

According to the fitting results, the strain sensitivity coefficient of the optical fiber is 0.049MHz/με.
4. Mechanical model

The relationship between optical fiber deformation and rock deformation can be regarded as a plane geometry problem. As shown in the figure, the sensing fiber is implanted into the rock stratum at a certain angle, and the included angle between the fiber and the rock stratum is $\alpha$.

![Figure 4. Schematic diagram of optical fiber implanted into rock stratum](image)

When the optical fiber is used to detect the floor heave of the roadway, the rock stratum of the roadway floor only changes vertically, so the optical fiber only changes vertically. The change of optical fiber during tunnel floor heave was shown in Figure 4.

The amount of strain deformation at any point $p$ on the optical fiber can be expressed by the following formula:

$$p' = p\varepsilon_p$$  \hspace{1cm} (3)

Where $p$ is the length of $P$ point on optical fiber; $\varepsilon_p$ is the strain of point $P$; $p'$ is $P$-point length variation.

The vertical variation of point $p$ can be expressed as:

$$p'_y = p'si\alpha$$  \hspace{1cm} (4)

The strain and variation on the whole optical fiber can be expressed as:

$$\Delta l = \int \varepsilon \, dz$$  \hspace{1cm} (5)

Where $\Delta l$ is strain variation of the whole fiber.

The variation of optical fiber in the vertical direction can be expressed as:

$$h = (l + \Delta l)\sin\alpha - Isina$$  \hspace{1cm} (6)

Where $h$ is a variation of optical fiber in a vertical direction; $l$ is the length of the whole fiber. There is little difference between $\alpha$ and $\alpha'$, to simplify the calculation, suppose $\alpha = \alpha'$, the above formula can be simplified as

$$h = \Delta Isina$$  \hspace{1cm} (7)

The formula (5) can be substituted into formula (7) to obtain:

$$h = \sin\alpha \int \varepsilon \, dz$$  \hspace{1cm} (8)

The optical fiber strain and vertical displacement of the rock stratum can be obtained by formula (8).

5. Indoor model application

To verify the accuracy of the above analysis, the similarity model was used to verify, the distributed optical fiber is embedded in the plane stress model, the sensing optical fiber is embedded in the rock mass, and the rock mass is in direct contact with the optical fiber. There is no adhesive material and no
The deformation of rock mass also pulls the optical fiber to be stressed and deformed. The plane model is carried out on a 3m long model frame. The simulated materials are sand, gypsum, and lime powder. The geometric similarity ratio of the model is $C_1=1:150$, and two vertical fibers are arranged, named FV1 and FV2 respectively. The vertical fiber is 850mm away from the model boundary. The specific layout of optical fiber is shown in the figure. The surface of the model is covered with speckles, and the deformation of rock mass is measured simultaneously by speckles and optical fiber during the experiment.

![Figure 5 Optical fiber layout](image)

During the test, the hydraulic supports made in equal proportion were put in the goaf of the working face, and the roof of the working face changed with the height of the hydraulic supports. The deformation of the roof was controlled by adjusting the height of the hydraulic supports.

After adjusting the height of hydraulic support five times, the strain measured by optical fiber and the displacement deformation measured by speckle at the same position is obtained. The following figure 6.

![Figure 7 Survey line DIC measured displacement and optical fiber calculated displacement](image)

(a)FV1 
(b)FV2

By comparing the data of the two images, it is found that the displacement change trend measured by FV1 distributed optical fiber is consistent with that measured by DIC, but there is a big difference in the data of the upper half of the line. The biggest difference is at 308mm above the optical fiber. The displacement change measured by BOTDA is 8.2 times that measured by DIC, and the difference between the two gradually decreases below 565mm of the line, and the data is consistent. The reason for this difference may be due to. The collapse of strata caused the incomplete contact between the
optical fiber and rock strata, resulting in slipping and falling off. The sand brittle material affects the contact area of the sensor and the effective transfer of strain. FV2 displacement change trend measured by 0-616mm distributed optical fiber is consistent with that measured by DIC, but the displacement change measured by DIC is larger than that measured by BOTDA in the large deformation stage of the lower part of the line. The main reason for this is that the large deformation of rock leads to the incomplete coupling between the optical fiber and the rock, resulting in the relative slip, and the displacement measured by the optical fiber is less than that measured by DIC.

6. Conclusion
(1) This paper presents a new method for monitoring floor heave. Compared with the traditional methods, the floor heave monitoring method can monitor the floor heave, which is not limited to the floor surface. This method can monitor the deformation of the strata at each stage of the bottom of the roadway.
(2) Through the formula proposed in this paper, the strain change measured by the distributed optical fiber embedded in the roadway floor can be transformed into the vertical displacement change, that is, the floor heave of the roadway can be obtained.
(3) Through the verification of the indoor similar model, the formula proposed in this paper can effectively measure the displacement variation of rock strata, and the coupling between optical fiber and rock strata determines the accuracy of the measurement results. The better the coupling between the optical fiber and rock, the more accurate the measurement results are.

References
[1] WU Jianxing,FANG Shulin. Mechanics mechanism and control technology of floor heave in dynamic pressure roadway in high-stress thick coal seam[J]. Coal Science and Technology,2018,46(12):86-91.
[2] GU Shuancheng,WANG Xingming,XUE Jiao,et al. Analysis of the relationship between floor heave deformation and abutment pressure in mining roadway of deep well[J]. Mining Safety & Environmental Protection,2021,48(1):44-49.
[3] KANG Hongpu,LU Shilian. Analysis of floor heave mechanism of roadway[J]. Journal of Rock Mechanics and Engineering,1991 (4):362-373.
[4] Gong P, Ma Z, Ni X & Zhang R. (2017). Floor heave mechanism of gob-side entry retaining with fully-mechanized backfilling mining. Energies, 10(12), 2085.
[5] ZHANG Guanyu,ZHAO Long,SHANG Yuqiang.Study on key control technology of floor heave in soft rock roadway[J].Coal Science and Technology,2019,47(11):63-67. doi: 10.13199/j.cnki.cst.2019.11.007
[6] L. Schenato, “A review of distributed fibre optic sensors for geo-hydrological applications,” AppliedSciences, 2017, 7(9): 896.
[7] Wang X, Shi B, Wei G, Chen S E, Zhu H, & Wang T. (2017). Monitoring the behavior of segment joints in a shield tunnel using distributed fiber optic sensors. Structural Control and Health Monitoring, e2056.
[8] Shi B, & Xing W. (2017). The monitoring of segments dislocation deformation in shield tunnel based on bofda. International Congress and Exhibition "Sustainable Civil Infrastructures: Innovative Infrastructure Geotechnology".
[9] Zhang, C.-C., Shi, B., Gu, K., Liu, S.-P., Wu, J.-H., Zhang, S., et al. (2018). Vertically distributed sensing of deformation using fiber optic sensing. Geophysical Research Letters, 45, 11,732–11,741.

[10] Cheng, G., Shi, B., Zhu, H. H., Zhang, C. C., & Wu, J. H. (2015). A field study on distributed fiber optic deformation monitoring of overlying strata during coal mining. Journal of Civil Structural Health Monitoring, 5(5), 553-562.

[11] Zhou W, Zhang P, Wu R, et al. Dynamic monitoring study on the characteristics of deformation and failure of extra-thick coal seam floor in deep mining[J]. Journal of Applied Geophysics, 2019.

[12] Chai, J., Du, W., Yuan, Q., & Zhang, D. (2019). Analysis of test method for physical model test of mining based on optical fiber sensing technology detection. Optical Fiber Technology, 48(MAR.), 84-94.

[13] J. Chai, X. Huo, Y. Qian, D. Zhang, Q. Yuan, and Y. Li, “Model test for evaluating deformation and weighting of overlying strata by distributed optical fiber sensing,” Journal of China Coal Society, 2018,43(S1): 36–43.