Research on the Layout and Data Processing Method of Distributed Optical Fiber in Shield Tunnel Monitoring

Yujie Li*, Qiang Li, Wenyong Shen and Lei Meng
China Beijing Subway Operation Co., Limited, Beijing 100044, China

*Corresponding author email: liyujie2566@bjsubway.com

Abstract. With the increase of subway service time, shield tunnels will produce different degrees of damage and destruction. This is related to external factors such as differences in stratum soil, groundwater seepage, construction disturbance to soil, and operating vehicle load. With the increase of subway service time, shield tunnels will produce different degrees of damage and destruction. This is related to external factors such as differences in stratum soil, groundwater seepage, construction disturbance to soil, and operating vehicle load. In order to ensure the operation safety of the subway, long-term and large-scale safety condition monitoring of the shield tunnel is very important. This study summarizes the technical characteristics, layout methods, data collection and processing of distributed optical fiber in shield tunnel deformation monitoring. The feasibility of distributed optical fiber monitoring technology is verified through the segmental deformation monitoring project of Beijing Metro Airport Line and Line 10 shield tunnel. In addition, some experiences in fiber layout and data processing are summarized, which has reference value for similar projects.

Keywords: Shield tunnel; Distributed optical fiber; Layout method; Data processing.

1. Introduction
Metro is an important part of urban rail transit. As an important part of subway engineering, shield tunnels have been widely used in many cities across the country. With the increase of service time, the tunnel structure has different degrees of damage and destruction during the operation due to the complex effects of external factors such as differences in the properties of the surrounding soil, groundwater seepage, vehicle loads, environmental temperature changes, and construction of adjacent subway structures. The damage and destruction are mainly manifested as cracking and shedding of the segment, crack expansion, uneven settlement of the tunnel structure, water and sand seepage, deterioration of the concrete, corrosion of the steel bars, etc. Once a safety accident occurs in a subway tunnel, it will produce inestimable losses. Therefore, the long-term, large-scale security status monitoring of shield tunnels becomes particularly important.

At present, traditional monitoring technologies such as total stations, level gauges, and static levels are widely used in tunnel deformation monitoring. These technologies are mainly manual operations, and mostly adopt point measurement, which cannot meet the continuity in space and time. Distributed optical fiber technology has the advantages of stable data transmission, high response sensitivity, strong electromagnetic resistance, corrosion resistance, and easy deployment. It can achieve continuity in space and time monitoring and is suitable for long-term deformation monitoring of tunnel structures[1].
2. Principle and Application Basis of Distributed Optical Fiber
The distributed optical fiber sensing technology based on Brillouin Optical Frequency Domain Analysis (BOFDA) calculates the frequency shift of Brillouin scattered light by testing a complex baseband transfer function. The baseband function is related to the amplitude of pump light and Stokes light traveling along the fiber.

The strain of optical fiber and Brillouin frequency shift can be expressed by the following formula

$$v_h(e) = v_h(0) + \frac{dv_h(e)}{de} \varepsilon$$

where $v_h(e)$ is the drift of the Brillouin frequency when strained to $\varepsilon$; $v_h(0)$ is the drift of the Brillouin frequency when the strain is 0; $dv_h(e)/de$ is the scale factor, about 493MHz (/% strain); $\varepsilon$ is the strain of the fiber.

Large-scale foundation projects, such as underground tunnels, viaducts, cross-river bridges, river embankments, and water conservancy hubs, will undergo varying degrees of deformation under various loads and external environments. There are two forms of deformation. One is large-scale or overall uniform and non-uniform deformation, such as settlement deformation of some structures, which is generally not easy to observe in the initial stage. The other one is local deformation mainly based on various cracks, mainly concentrated in The stress concentration area of the structure. The width of the fissures is small and unevenly distributed, and the strain is often only on the order of $10^{-5}$ to $10^{-7}$. It is more suitable for monitoring the above deformation with distributed optical fiber monitoring technology based on BOFDA[2]. The development and application of this technology have great practical significance for the safety monitoring and health diagnosis of structures.

3. Distributed Optical Fiber Deployment
The distribution of distributed optical cables can be divided into two categories, including comprehensive layout and fixed-point layout. The former refers to the layout by pasting, grooving or pre-buried into the structure, and the latter refers to the layout fixed by means of snaps, clips, etc[3]. The monitoring projects of Beijing Metro Airport Line and Line 10 shield tunnel are based on the relative displacement and relative misalignment of segments. Considering the discontinuity of the shield tunnel structure, the fixed-point layout method was chosen.

3.1. Selection of Distributed Optical Fiber
According to the site conditions and monitoring project requirements, polyurethane strain sensing fiber and fixed-point fiber are selected, as shown in Fig. 1.

3.2. Design of Optical Fiber Layout
In order to monitor the relative displacement of the segments, a fixed-point optical cable and a distributed temperature-measuring optical cable were laid axially on the right waist line of the tunnel. The fixed-point optical cable needs to be pre-stretched, and the temperature-sensing optical cable remains free. The fixed-point optical cable is fixed with a buckle. The layout of the optical cable is shown in Fig. 2.
The optical cable for monitoring the uneven settlement of the segment is arranged at the waistline side of the tunnel. The optical cables are laid out in a "Z" shape along the side walls of the tunnel, as shown in Fig. 3(a). The custom-made fixed disk is shown in Fig. 3(b).

Figure 2. Optical cable arrangement for monitoring relative displacement.

4. Data Collection and Processing
The focus of distributed optical fiber data collection and processing is the division and precise positioning of data segments. This is a prerequisite for positioning of the joint of the segment and positioning of the optical fiber cable.

4.1. Fiber Optic Data Collection
There are three main fiber optic strain monitoring and sensing technologies based on Brillouin scattering[4]: Brillouin Optical Time Domain Reflectometer (BOTDR), Brillouin Optical Time Domain Analysis (BOTDA) and Brillouin Optical Frequency Domain Analysis (BOFDA). The high-precision BOFDA demodulation device fTB2505-BOFDA is used in this study. The equipment requires optical fibers to form a closed loop for data collection. Compared with the single-line data acquisition method of other equipment, the spatial positioning accuracy of this equipment is higher. The working mode of fTB2505-BOFDA is shown in Fig. 4.

Figure 4. Working mode of fTB2505-BOFDA.

In order to ensure the timeliness and reliability of optical fiber data, the data collection efficiency and qualification rate should be improved. After the optical fiber is installed, the FC interface of the jumper should be kept clean, and wiped with clean paper dipped in alcohol before each use to ensure the qualification rate of the collected data. When collecting data for the first time, the effective monitoring frequency interval and corresponding step distance of the optical fiber should be obtained first by means of instrument self-test. Then the corresponding parameters of the fiber frequency scanning interval and the fiber frequency scanning step should be modified to improve the efficiency of data collection.
4.2. Determination of Effective Measurement Section of Optical Fiber
Considering that the optical fiber needs to be reserved with sufficient length for connecting to the optical fiber demodulation device, the actual fiber length is generally longer than the length of the effective measurement section to be monitored, so how to determine the effective measurement section of the fiber is particularly important. The effective measurement section of the optical fiber can be determined by combining the graphical characteristics of the optical fiber monitoring data and the way of applying prestress at both ends of the optical fiber on site. By applying prestressed starting and ending points on both ends of the effective monitoring interval of the optical fiber, the monitoring position was finally determined. The effective measurement section between the abrupt positions of the optical fiber monitoring data pattern is 498.4528m, as shown in Fig. 5.

4.3. Segmentation of Optical Fiber Data
In order to obtain the segment deformation at the splicing position of each segment, the optical fiber needs to have an accurate positioning function. Therefore, the segmentation of optical fiber data is very important. The optical fibers in this study are all fixed-point layout. Data segmentation can be divided into the theoretical data segment of the optical fiber according to the abrupt change of the optical fiber data pattern and the factor of superimposing the fixed point length. However, due to the complexity of on-site layout conditions, the division of the theoretical optical fiber data segment is different from the actual one. On-site verification or correction is necessary. As shown in Fig. 6, by prestressing the optical cable, abrupt fiber data patterns can be obtained, and the data segmentation can be verified or corrected.

![Figure 6. Prestress application and curve verification.](image)

(a) prestress on fixed-point optical cable  (b) fiber optic data curve  (c) curve after applying prestress

4.4. Data Processing
Optical fiber processing errors and optical fiber measurement errors may cause fixed-point fiber data to shift at fixed-point positions, which makes the data on both sides of the fixed point position mutate and produce noise, as shown in Fig. 6(c). The green and red curves in Fig. 6(c) respectively represent two different fixed-point optical fiber data graphs. The enlarged curve is shown in Fig. 6(c). The two lines are staggered by about 5cm in the horizontal direction, which is a minimum identifiable data segment length. Therefore, the first step in data processing is noise reduction. In this paper, the segmented fixed-point optical fiber data is retracted from the fixed-point position by two data segments as normal data to participate in the subsequent calculation.

The second step of data processing is to eliminate outliers. There are three obvious outliers in Fig. 7. After field investigation, it is known that the data anomaly is caused by the abnormal state during installation, such as the fiber crossing the obstacle. Such abnormal points should be eliminated so that the strain varies between $-60\mu\varepsilon$ and $90\mu\varepsilon$. In addition, the above-mentioned situation should be avoided as much as possible when laying optical fibers on site.
The discrete data in the data is eliminated by the consistency elimination discrete algorithm. The average value of the first three monitoring data is used as the initial value. The difference between the subsequent monitoring data and the initial value is the strain of the measuring point. Distributed optical fiber monitoring is affected by temperature changes. According to the temperature influence coefficients of different optical fibers, temperature compensation is performed on the optical fiber data. The strain data after temperature compensation is shown in Fig. 8.

**Figure 7.** Abnormal strain value.

**Figure 8.** Strain of fixed-point optical cable for Beijing Metro Line 10.

5. Conclusion

This study summarizes the technical points in the process of optical fiber deployment and data processing by monitoring the segment of Beijing Metro Airport Line and Line 10 shield tunnel. The specific conclusions are as follows:

1. During the installation of distributed optical fiber, the installation location should be reasonably selected, and obstacles should be avoided as far as possible to prevent the impact on the data. If the obstacle cannot be avoided, the optical fiber should remain free. The data at this location should be removed in subsequent processing.

2. In order to improve the accuracy of distributed fiber monitoring, temperature compensation fiber data should be added on the basis of fixed-point fiber calculation to modify.

3. When the frequency scanning interval and scanning step of the optical fiber are the frequency interval corresponding to the effective measurement segment of the optical fiber and the step required for monitoring accuracy, the observation efficiency can be significantly improved.

4. The cleanliness of the FC interface of the fiber jumper is the guarantee of data reliability. This technology has a positive effect on shield tunnel monitoring and helps promote the development of tunnel monitoring related research.
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