Research on Algorithm and Application of Shield Tunnel Distributed Optical Fiber Monitoring Data

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Abstract. Shield tunnels have different degrees of damage due to the differences in the surrounding soil properties, the disturbance of the soil during construction and the repeated loading of vehicles during operation, and there is a tendency to deteriorate with the increase of subway service time. The long-term and large-scale security status monitoring of shield tunnels is an important guarantee for the safety of subway operation. Two diagnostic algorithms based on strain monitoring data are proposed in this paper, one is for the openness and dislocation of the segments, and the other is for the uneven settlement of the tunnel. The effectiveness of the two algorithms is verified by distributed optical fiber monitoring data of Beijing Metro Line 10. The calculation results are also compared with traditional monitoring methods. The proposition of these two algorithms provides a new idea for the analysis of distributed optical fiber shield tunnel monitoring data, which is beneficial to the promotion of distributed optical fiber monitoring technology.

Keywords: Shield tunnel; Distributed optical fiber; Differential settlement; Diagnostic algorithm.

1. Introduction
With the acceleration of urbanization in China, the problem of traffic congestion is becoming more and more serious. Many cities have subway lines. Shield tunnels have been widely used as an important part of subway projects[1]. In the process of construction and normal operation of the subway tunnel project, different degrees of damage and destruction are generated in shield tunnels due to the difference in the nature of the surrounding soil under the shield tunnel structure, the disturbance of the soil during construction and the repeated loading of the vehicles in operation[2]. Metro tunnel safety accidents will produce incalculable losses. Therefore, it is very important to monitor the long-term and large-scale safety status of shield tunnels[3].

In the current tunnel structure monitoring method, distributed optical fiber can monitor the deformation during subway construction and operation in real time and continuously due to its advantages of real-time, anti-interference and durability[4]. This paper presents two algorithms for optical fiber monitoring data, and is applied in the distributed optical fiber monitoring of Beijing Metro Line 10. The method is verified in the feasibility of segment dislocation, openness and uneven settlement monitoring of tunnels.

2 Algorithm Theory of Distributed Optical Fiber in Shield Tunnel Monitoring Data
The algorithm proposed in this paper includes two types, one is the strain analysis method of distributed optical fiber monitoring data for shield tunnel segment dislocation and openness disease, and the other is...
the uneven settlement diagnosis of the tunnel structure based on the longitudinal multi-point strain angle algorithm.

2.1. Strain Analysis
The essence of the algorithm is to calculate the deformation directly from the strain data monitored by the optical fiber.

The measurement error of distributed optical fiber monitoring data mainly comes from the error of the environment and the measurement error of the optical fiber itself. Between them, the error of the external environment is mainly caused by temperature, which can be corrected by the temperature compensation fiber data; the measurement error of the fiber itself requires a large amount of measurement data combined with traditional instrument measurement data for analysis. For example, when the optical fiber data curve after temperature compensation correction fluctuates within ± 20 με, but the deformation is basically stable after monitoring with traditional instruments, it proves that the fluctuation within ± 20 με belongs to the measurement error of the optical fiber itself.

After eliminating the distributed fiber measurement error, the deformation can be obtained according to the micro-strain of the fiber, as shown in Eq. (1).

\[ \Delta L = \overline{\varepsilon}L \]  

(1)

where \( \Delta L \) is the amount of fiber stretch; \( L \) is the length of the fiber; \( \overline{\varepsilon} \) is the average value of the strain of the fiber. According to Eq. (1), the deformation of the fiber along the axial direction of the tunnel segment can be calculated, which is the openness of the segment. Similarly, the vertical deformation of the optical fiber along the tunnel segment can also be calculated, which is the longitudinal displacement value of the segment.

2.2. Diagnosis Algorithm for Uneven Settlement of Tunnel Structure
This method is a probabilistic statistical algorithm that can be calculated based on strain data monitored by optical fibers. Here below is the idea of the algorithm:

Firstly, the surrounding rock grade of the tunnel is classified according to the characteristics of the rock or soil surrounding the shield tunnel. The distributed optical fiber monitoring data corresponding to the same surrounding rock grade is divided into one category. Then the SVM (Support Vector Machine) monitoring data of the same surrounding rock grade is divided into several categories according to the similarity of the measurement points.

Secondly, since the structural strains of the measuring points in the same class distributed along the longitudinal direction have a good correlation, the measuring points of the same class can be finely divided into different sections according to a certain standard. Taking the strain vector formed by the measurement points of each section as the calculation unit, the vector angle between adjacent sections can be calculated. The angle between each segment of vectors constitutes the angle vector corresponding to the same type of monitoring data.

Thirdly, taking the angle vector at the initial observation time as a sample, the tunnel sample set in a healthy state can be obtained and used as the initial value of strain. The Mahalanobis distance of the initial value is used as the diagnostic factor for uneven settlement of the tunnel structure, and the corresponding diagnostic threshold is delineated.

Finally, the strain monitoring data is substituted and the corresponding angle vector and diagnostic factor for uneven settlement are obtained. Compare with the corresponding diagnostic threshold in the healthy state to determine whether the tunnel structure has uneven settlement in this state.

3. Analysis of Distributed Optical Fiber Monitoring Data of Shield Tunnel
Taking distributed optical fiber monitoring data of Beijing Metro Line 10 as an example, the above algorithm is used to analyze the results.

3.1. Analysis of Segment Openness
The fixed-point optical fiber is laid along the waist position of the tunnel segment. Taking the initial monitoring data of the fixed-point optical fiber monitoring point as the reference value, the difference
between the monitoring data of each measurement point and the reference value in the subsequent observation time is calculated by the strain and deformation analysis method, and then the difference in strain is obtained. The final monitoring result is the difference between the fiber length and the deformation. During the calculation, the temperature of the monitoring data needs to be corrected. The location of the abnormality of the openness of the segment finally obtained is shown in Fig. 1.

![Figure 1. Monitoring results of the segment openness.](image1)

Results of the openness over-limit of line 10 segment showed that there were abnormal mutations in the interval of 93 ~ 95, 136 ~ 137, 185 ~ 186. Construction records show that the anomaly sections 93 ~ 95 and 185 ~ 186 are the tie rod section and the cross-line section, respectively, and the monitoring data has been greatly changed by the influence of fiber installation factors. The time-history curve of the anomaly segment 136 ~ 137 shows that this segment has undergone about 2.4mm since April, and the data tends to be stable in the later period. The on-site inspection results present that the buckle of the fixed optical fiber in this section is loose, which is the reason for the large data, and the openness of the segment is normal. After removing outliers, the deformation after conversion is within ± 0.12mm.

3.2. Analysis of Segment Dislocation
Taking "Z" shaped fiber monitoring data as an example, the strain deformation analysis method was used to obtain the fiber deformation between adjacent tube segments. Combined with the included angle of the fiber layout, the longitudinal displacement of the segment can be calculated. Fig. 2 shows the fiber layout.

![Figure 2. Layout of distributed optical fiber.](image2)

In this study, the longitudinal displacement of the segment is the differential settlement of the segment in the longitudinal direction. Similar to the openness analysis method of the segment, the abnormal position of the segment dislocation is shown in Fig. 3.

![Figure 3. Monitoring results of the segment dislocation.](image3)
Results show that the differential settlement limit of the segment is between 209.06 ~ 227.46m, 249.86 ~ 255.84m, and 546.51 ~ 552.74m. The above three sections are all tie-bar sections or cross-line sections, and the monitoring data is greatly affected by the installation factors of the optical fiber. After removing outliers, the conversion distortion is within ± 0.06mm.

3.3. Analysis of Uneven Settlement of Tunnel

Taking the "Z" shaped fiber monitoring data as an example, the uneven settlement of the tunnel structure is analyzed using a longitudinal multi-point strain angle diagnosis algorithm. The "Z" shaped fiber monitoring data is converted into longitudinal strain data, and substituted into the SVM algorithm for classification. The longitudinal strain data after classification is substituted into the tunnel uneven settlement diagnosis algorithm according to the category for calculation. Combined with the site conditions, the influence range of the uneven settlement of the tunnel structure is generally 5.2m. 5.2m is used as the dividing distance of the tunnel structure segment to refine the subdivision, so as to calculate the angle vector. Firstly, the data under the entire monitoring period is divided into two parts. The first 50% of the monitoring period is the state of health, and the remaining monitoring period is the state to be diagnosed. Secondly, the angle between the strain vectors of the measuring points in the adjacent tunnel structure sections under the healthy state and the state to be diagnosed is calculated. The diagnostic factors D and D' of the uneven settlement of the tunnel structure are calculated in both states, and the diagnostic threshold D'' for the healthy state is also determined. Finally, the diagnosis factor D' of the uneven settlement of the tunnel structure to be diagnosed is compared with the diagnostic threshold D'' of the healthy state. If D' > D'', the uneven settlement has occurred, otherwise it has not.

The diagnosis results of the strain data of each type of structural section of an adjacent tunnel are shown in Fig. 4. Results showed that the data to be diagnosed did not exceed the diagnostic threshold, indicating that the tunnel structure in the monitoring area did not undergo uneven settlement.

![Monitoring results of the segment.](image)

**Figure 4.** Monitoring results of the segment.

Diagnosis results of different types of tunnel structures are organized into a complete diagnosis matrix of uneven settlement of tunnel structures. The diagnosis result matrix of the uneven settlement of the tunnel structure is 0/1, where 0 indicates that the tunnel structure has not undergone uneven settlement, and 1 indicates that the tunnel structure has undergone uneven settlement. The cell where the number 0 is located is covered with green, and the cell where the number 1 is located is covered with red. Finally, the diagnosis result of uneven settlement of the entire tunnel structure is visualized as shown in Fig. 5. Results show that the tunnel structure is still in a healthy state. The tunnel structure was diagnosed as abnormal at an individual moment due to the abnormality of the measured data at that moment.

![Layout of distributed optical fiber.](image)

**Figure 5.** Layout of distributed optical fiber.
3.4. Comparison with the Results of Traditional Monitoring Methods

The changes of the segment and tunnel configuration calculated by the above two algorithms are compared with the data obtained by traditional monitoring methods. Figure 6 shows a comparison diagram of segment misalignment. The acronyms on the right of the figure represent different measuring points. The trend of distributed fiber monitoring results is consistent with traditional methods. The accuracy of the algorithm is verified, which shows that the algorithm is reliable.

![Comparison of monitoring results between distributed optical fiber and traditional methods.](image)

Figure 6. Comparison of monitoring results between distributed optical fiber and traditional methods.

4. Conclusion

This paper proposes an algorithm for calculating deformation based on strain for the openness and dislocation of segments. In addition, a diagnosis algorithm that directly analyzes strain is proposed for the uneven settlement of the tunnel. The calculation method is applied in the distributed optical fiber monitoring data of Beijing Metro Line 10. The calculation results are compared and verified with traditional monitoring methods. The proposition of these two algorithms provides a new idea for the analysis of the distributed optical fiber monitoring data of shield tunnels at present, which is beneficial to the promotion of distributed optical fiber monitoring technology.

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