Deformation monitoring of ultra-deep foundation excavation using distributed fiber optic sensors

Ren Bangke1,2,*, Zhu Hehua1,2, Shen Yi1,3, Zhou Xiaozhou1,3, Zhao Tengteng4

1 State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
2 State Key Laboratory of Disaster Reduction in Civil Engineering, Tongji University, 1239 Siping Road, Shanghai 200092, China
3 Key Laboratory of Geotechnical and Underground Engineering of the Ministry of Education, Tongji University, 1239 Siping Road, Shanghai 200092, China
4 Shanghai SMI Water Group Co., Ltd., 888 Guilin Road, Shanghai 201103, China

Abstract. The development and utilization of urban underground space is producing a large number of deep foundation pits. On-site monitoring is a key issue to ensure the safety of the foundation excavation, especially the monitoring of the horizontal displacement of the structure. The rapid development of distributed fiber optic sensors technology in recent years could avoid the deficiencies of manual monitoring methods, which can quickly, real-time and continuously monitor the horizontal displacement of deep soils. At the same time, with the support of the information platform, the monitoring data can be transmitted back to the computer terminal to realize remote monitoring. This paper relies on the ultra-deep circular foundation excavation project (58.65m deep, the deepest foundation pit in Shanghai) in the test section of the Suzhou River deep tunnel, and uses the distributed optical fiber monitoring technology of Brillouin optical frequency domain analysis (BOFDA) to monitor the horizontal displacement of the deep foundation. This paper introduces the process, methods and precautions of optical fiber monitoring from early installation, equipment debugging to data acquisition, data processing and data analysis. The analysis results not only obtained the deformation law of ultra-deep foundation excavation, but also proved the advantages of optical fiber monitoring in deep foundation excavation. Finally, the data has been uploaded to the digital platform for remote monitoring in the future.

Keywords: Ultra-deep foundation, Optical fiber monitoring, The horizontal displacement.

1 Introduction

Traditionally, the horizontal displacement is measured using Levels and inclinometers. However, due to the influence of artificial factor, this process has large accidental errors and takes a long time. Distributed fiber optic technology is a new type of photoelectric sensor monitoring technology advanced rapidly over the last decade and have been applied successfully to the health monitoring of geotechnical structures. When compared to the traditional measurement method, it allows for real-time monitoring of the horizontal displacement of deep soil and can also measure the strain at an optional point and the strain distribution in the lengthwise direction of an optical fiber. In addition, the network can transmit the monitoring data back to the computer terminal in real time, which makes it possible for remote monitoring combined with information platform.

Currently, the most popular distributed optic fiber sensing technology in the field of underground engineering health monitoring, which are totally based on Brillouin scattering, mainly include three kinds: Brillouin optical time domain reflectometry (BOTDR), Brillouin optical time domain analysis (BOTDA) and Brillouin optic
frequency domain analysis (BOFDA). These three technologies all use the linear relationship between the frequency shift of the Brillouin backscattered light in the optical fiber and the changes of temperature and strain to realize sensing, but the difference is their method of obtaining the Brillouin frequency shift. BOTDR and BOTDA have been widely used around the world, and BOFDA also exhibited excellent performance on strain measurement accuracy.

Lu et al. introduced the application of a BOTDR-based technology to measure the stress within precast piles[1]. Ding et al. presented a new method to monitor the deformation state of the SMW pile under the stress based on BOTDA, it is proved that the method has good field adaptability and can obtain real-time strain data in the actual foundation engineering[2]. In terms of tunnel engineering, Wang et al. applied the BOFDA to the Suzhou Metro Line 1 tunnel for tunnel lining segment joint monitoring[3]. An actual applied system for monitoring tunnel changes is discussed by Komatsu et al. [4], including tunnel longitudinal strain and tunnel sectional displacement. Existing research has proved the advantages of distributed optical fiber technology compared with traditional monitoring methods in on-site monitoring of Geotechnical engineering.

For the ultra-deep excavation, on-site monitoring is an indispensable part of information construction. Wang et al. attempted to discuss the evolution characteristics of an ultra-deep foundation pit in Beijing (31.4m deep) with a combination of numerical simulation and in situ monitoring [5]. Zhang et al. monitored and analyzed the deformation of a deep foundation pit in Anyang, China, and introduced the space-time effect of foundation pit deformation [6]. China’s deep foundation excavation has constantly updated various records, a more real-time, more accurate and more convenient monitoring technology is needed to match.

This paper presents a research on the monitoring of the deformation of ultra-deep foundation excavation based on BOFDA, rely on the ultra-deep circular foundation excavation engineering (58.65m deep) in the test section of Suzhou River deep tunnel in Shanghai. Taking the horizontal deformation as an example, the integrated optical fiber monitoring program for deep foundation excavation was discussed, from early installation, equipment debugging to data collection and data analysis. On this basis, combined with the digital platform, the feasibility of remote real-time acquisition and analysis of distributed optic fiber monitoring is discussed.

2 Monitoring Principle

2.1 Principle introduction of BOFDA

BOFDA technology calculates the frequency shift of Brillouin scattered light by measuring the response of a complex baseband transmission function. The frequency shift of Brillouin scattered light is affected by strain and temperature at the same time. When the temperature along the fiber changes or there is axial strain, the frequency of the back Brillouin scattered light in the fiber will drift, whose amount has a good linear relationship with the change of strain and temperature. Therefore, the temperature and strain distribution information along the optical fiber can be obtained by measuring the frequency drift of the back Brillouin scattered light.

The optical fiber demodulator used in this foundation engineering is a FTB2505 manufactured by fibrisTerre, with an ultra-high spatial resolution of 20 cm, a strain accuracy of ±2 με, and a dynamic range of more than 20 dB, which meets the monitoring requirements of a deep foundation pit.

2.2 Calculation principle of deflection

The deflection of the bending deformation of the structure can be calculated from the strain value of the optical fiber sensor inside the structure. Figure 1 shows the deformation diagram of pile body subjected to horizontal load.
Fig. 1. Deformation diagram of pile body subjected to horizontal load.

The axial compressive strain $\varepsilon_a(z)$ and the bending strain $\varepsilon_m(z)$ can be expressed as:

$$\varepsilon_a(z) = \frac{\varepsilon_1 + \varepsilon_2}{2} \quad (1)$$

$$\varepsilon_m(z) = \frac{\varepsilon_1 - \varepsilon_2}{2} \quad (2)$$

where $\varepsilon_1$ and $\varepsilon_2$ respectively are the strain values of the symmetrical part along the horizontal load direction of the pile at the depth $z$ obtained by the test. The radius of curvature of the line segment $O_1O_2$ on the neutral layer is $\rho(z)$. According to the relationship between bending strain and pile radial displacement, in the case of small deformation, the deflection curve of the pile is a gentle curve. The deflection can be calculated by Equation (3):

$$\omega(z) = -\int_{H}^{Z} \int_{H}^{Z} \frac{\varepsilon_m(z)}{\gamma(z)} dzdz - Cz - D \quad (3)$$

where $\omega(z)$ is the deflection of pile at the depth of $z$, $C$ and $D$ are undetermined coefficients, $H$ is the pile depth, which can be determined by the boundary conditions of the pile body.

3 Project Summary

The monitoring project is carried out based on the test section of Suzhou River deep tunnel in Shanghai. This project plans to build a super large drainage tunnel with a diameter of 10m, a buried depth of 50-60m, and a length of about 1.67km under the Suzhou River. whose volume mainly includes the Miaopu Vertical Shaft, the Yunling Vertical Shaft and the Shield Tunnel.

The Yunling Vertical Shaft is a ultra-deep circular foundation excavation engineering (58.65m deep), which refreshed the current record of excavation depth in soft soil areas in China. In order to verify the feasibility of BOFDA-based optical fiber remote monitoring, the lateral displacement of the ground wall of the shaft was instrumented. Figure 2 shows the construction site and the subdivision plan view of the underground continuous wall of the maintenance structure including distribution of measuring points. The thickness of the underground continuous wall is 1.0m to 1.5m and the depth is 103m, totaling 80 sheets. The red mark is the optical fiber installation position, which corresponds to the P-03 measuring point of manual monitoring.
On the monitoring section of the diaphragm wall, as shown in Figure 3, optical fiber sensors need to be arranged on the front and rear steel cages, and the U-shaped strain sensing optical cable layout is adopted, which requires a total of 220m distributed strain sensing cables. At the same time, a temperature compensation sensing cable is laid for temperature compensation within the excavation range, and its length is also 220m.

In the monitoring section, the lining of the circular foundation pit of the shaft adopts the top-down method, which is divided into 15 layers of excavation. After the excavation of each layer is completed, optical fiber monitoring is required, and in specific precipitation, corresponding monitoring will also be carried out. The optical fiber was monitored for the first time on October 25, 2019, and this data was used as the initial monitoring value; the last monitoring was performed after the excavation of the last layer of the foundation pit on December 28, 2020. To the end of the excavation, a total of twenty times optical fiber monitoring was carried out, which lasted more than 1 year.

4 Analysis of monitoring data

4.1 Data collection and processing

In the process of data acquisition, the value read each time is the strain data and the temperature data within the entire length of the U-shaped optical fiber. The data pre-processing for the initial data is mainly completed on the distributed optical fiber sensing data processing system developed by Nanzee Sensing Technology Company. The main operations include data format conversion, effective data area interception, data smoothing and denoising, difference with initial data, accurate extraction of strain and temperature at the same depth and temperature compensation, etc. After these, the true strain of the optical fiber is output.
The confined water layer that is mainly considered in the construction is located between 40.8 meters and 46.2 meters. The table 1 introduces the excavation details. The monitoring time is mainly selected at the end of the excavation of each layer of soil.

| Date       | Number | Excavation depth | Weather | Working condition                                      |
|------------|--------|------------------|---------|-------------------------------------------------------|
| 2020/4/6   | M1     | 17.05m           | sunny   | The third layer excavation is over                    |
| 2020/4/16  | M2     | 17.05m           | sunny   | The third layer of ring beam maintenance              |
| 2020/4/29  | M3     | 21.55m           | sunny   | The fourth layer excavation is over                   |
| 2020/5/11  | M4     | 23.40m           | loudy   | The fourth layer is being excavated                   |
| 2020/5/25  | M5     | 26.05m           | loudy   | The fifth layer excavation is over                    |
| 2020/6/1   | M6     | 26.25m           | sunny   | The sixth layer is being excavated                    |
| 2020/6/11  | M7     | 26.70m           | sunny   | The sixth layer is being excavated                    |
| 2020/6/22  | M8     | 29.05m           | loudy   | The sixth layer excavation is over                    |
| 2020/7/8   | M9     | 29.85m           | loudy   | Before excavation of the seventh layer                |
|            |        |                  |         | (After continuous rain)                               |
| 2020/7/17  | M10    | 32.85m           | loudy   | The seventh layer excavation is over                  |
| 2020/7/28  | M11    | 32.85m           | sunny   | Seventh layer maintenance construction                |
| 2020/8/11  | M12    | 35.85m           | rainy   | The eighth layer excavation is over                   |
| 2020/8/29  | M13    | 35.85m           | sunny   | Before excavation of the ninth layer                  |
| 2020/9/10  | M14    | 38.85m           | sunny   | The ninth layer excavation is over                    |
| 2020/9/27  | M15    | 42.45m           | sunny   | The tenth layer excavation is over                    |
| 2020/10/20 | M16    | 45.45m           | loudy   | The eleventh layer excavation is over                 |
| 2020/11/6  | M17    | 48.45m           | sunny   | The twelfth layer excavation is over                  |
| 2020/12/1  | M18    | 51.45m           | sunny   | The thirteenth layer excavation is over               |
| 2020/12/28 | M19    | 58.65m           | loudy   | The fifteenth layer excavation is over                |

4.2 Analysis of results

Figure 4 shows the horizontal displacement curve of the foundation pit during the nineteenth fiber monitoring process. It can be found that the overall result of fiber optic monitoring is the same as expected, showing an obvious bulging deformation mode.

Fig. 4. Horizontal displacement curve during the monitoring process.
The maximum displacement is mainly concentrated between 40 meters and 50 meters. In the early stage of excavation (from May to June), the maximum displacement gradually increases with the increase of excavation depth. In the intermediate stage of excavation (from July to September), there is a tendency to decrease first and then remain stable. At this time, the deformation of the foundation pit is mainly affected by the precipitation inside and outside the pit. In the later stage of excavation (from October to December), the displacement shows an increasing trend with the excavation, and reaches its maximum at the end of the excavation of the foundation.

Figure 5 summarizes the relationship between the excavation depth $H$ and the maximum lateral displacement of structure. According to the result, although the foundation pit is an ultra-deep foundation pit and its excavation depth is much greater than other foundation pit projects in Shanghai, its deformation range is only between 0.019% and 0.042%, which is far less than the 0.18%H of the Shanghai level I control standard. Considering that the shaft is a circular structure and the overall structure has stronger bending resistance, so the lateral direction is well controlled.

![Graph showing the relationship between excavation depth and maximum lateral displacement](image)

**Fig. 5.** Relationship between the excavation depth $H$ and the maximum lateral displacement.

Figure 6 shows the result of comparison between the selected optical fiber monitoring and manual monitoring at the same time. Results of the two types of monitoring are similar in an overall trend, but there’s a main difference reflects in the depth of 80 meters to 100 meters. The displacement of the artificial inclinometer at the deepest part of the enclosure structure is not zero, which may be inconsistent with the actual situation. Through the comparison of the data, it can be found that the deeper the excavation is, the better the consistency of the optical fiber monitoring and manual monitoring results will be obtained.
Fig. 6. Comparison between fiber monitoring and manual monitoring at the same time (a) M5 (2020.5.25) (b) M16 (2020.10.20) (c) M19 (2020.12.28).

5 Conclusions

In this study, a BOFDA-based fiber optic monitoring technique was successfully applied to the Deformation monitoring of a ultra-deep foundation excavation. The test results fully show the distributed and high-precision advantages of the fiber sensing technology. Related monitoring data have been uploaded to the digital platform, related monitoring data have been uploaded to the digital platform. On this basis, follow-up will carry out more in-depth research on remote monitoring.

References

1. Lu, Y., Shi, B., Wei, G. Q., Chen, S. E., Zhang, D.: Application of a distributed optical fiber sensing technique in monitoring the stress of precast piles. Smart Materials & Structures 21(11):115011(2012).
2. Ding, Y., Wang, P., Yu, S.: A new method for deformation monitoring on H-pile in SMW based on BOTDA. Measurement 70:156-168 (2015).
3. Wang, X., Shi, B., Wei, G., Chen, S. E., Zhu, H., Wang, T.: Monitoring the behavior of segment joints in a shield tunnel using distributed fiber optic sensors. Struct Control Health Monit 25:e2056 (2018).
4. Komatsu, K., Fujihashi, K., Okutsu, M.: Application of optical sensing technology to the civil engineering field with optical fiber strain measurement device (BOTDR). In: Proceedings of SPIE - The International Society for Optical Engineering, 4920 (2002).
5. Wang, S. D., Li, Q. M., Dong, J. M.: Comparative investigation on deformation monitoring and numerical simulation of the deepest excavation in Beijing. Bulletin of Engineering Geology and the Environment 80(3) (2020).
6. Zhang, X.: Deformation analysis of deep foundation pit excavation in China under time–space effect. Geotechnical Research 7(3): 146–152 (2020).