Distributed Fiber Optic Sensing in Pile Load Tests: Technological Development and Applications

Hong-Hu Zhu[1,2](✉), Jing Wang[1], Bin Shi[1], and Guang-Qing Wei[3]

[1] School of Earth Sciences and Engineering, Nanjing University, Nanjing, China
zhh@nju.edu.cn
[2] Institute of Earth Exploration and Sensing, Nanjing University, Nanjing, China
[3] Suzhou Nanzee Sensing Technology Co., Ltd., Suzhou, China

Abstract. Piles enable a safe and convenient solution for providing adequate bearing capacity for civil infrastructures, which can be individually customized to changing soil conditions. Fully instrumented piles with advanced monitoring techniques can offer new insights into the bearing capacity and structural integrity of piles in field tests. Recently distributed fiber optic sensing (DFOS) technologies provide a powerful tool for geotechnical monitoring by enabling distributed and automatic strain measurement along fiber optic (FO) cables. This paper presents the DFOS-based pile monitoring system, which helps to quantify and refine each step during pile testing. According to the construction characteristics of precast piles, bored concrete piles and steel piles, various installation methods of FO cables on piles are introduced, respectively. Two case studies are illustrated to show the capability of DFOS in monitoring the performance of axially and horizontally loaded piles.

Keywords: Distributed fiber optic sensing (DFOS) · Field instrumentation · Pile load tests · Geotechnical monitoring · Interfacial behavior

1 Introduction

With the continuous acceleration of urbanization in Belt and Road countries and regions, super high-rise buildings, deep underground structures, large bridges, and other civil infrastructure are being built in major cities. Piles are common deep foundations used to transmit loads through shallow soil of low bearing capacity to deep soil or rock strata [1, 2]. However, as piles are embedded in ground soils, there is great difficulty in detecting their behavior, integrity, and load transfer properties. The existing detection methods cannot meet the increasing demand of engineering practice.

Static pile load tests are the basic and reliable method to understand the actual performance of piles in the field and obtain the relevant geotechnical parameters. For instance, the compressive, pullout and horizontal bearing capacity of piles can be determined based on the load-displacement curves, which are very important for optimizing pile design schemes. Appropriate instrumentation is required to get reliable measurements

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so that the deformation and loading conditions of the instrumented piles can be evaluated [3–5]. Conventional sensors include extensometers, load cells, and vibration-wire strain gauges. However, these point-type sensors can only provide discrete information on the pile performance. The installation is tedious and may affect the pile integrity due to a large number of communication cables. In addition, conventional sensors often require substantial protection measures.

In recent years, a critical advance in geotechnical instrumentation is the wide applications of distributed fiber optic sensing (DFOS) technologies, which bring a new concept and methodology for measuring the behaviors of shallow and deep foundations due to their continuous nature [6–9]. In the past three decades, a number of DFOS technologies have been successfully used for pile monitoring, such as the fiber Bragg grating (FBG) [10–12], Brillouin optical time-domain reflectometry (BOTDR) [13–20], Brillouin optical time-domain analysis (BOTDA) [21–23], Brillouin optical frequency-domain analysis (BOFDA) [24, 25], and optical frequency domain reflectometry (OFDR) [26]. Among them, the Brillouin scattering-based technologies can perform fully distributed strain sensing of pile behavior. In the UK, the BOTDR technique was used to monitor the performance of a secant pile wall subjected to multiple props during construction of an adjacent basement, which can also obtain the axial force and a bending moment of the pile and then obtain the axial and lateral movement of the pile [15]. Distributed fiber optic sensors can also be accomplished to obtain strain profiles along piles during pile driving, which is helpful to reveal the failure mechanism of displacement piles [19, 24]. In China, the quasi-distributed FBG sensors were packaged into various types to monitor pile deformation, internal force and earth pressure near the pile [12, 21]. Using FBG sensing systems, elaborate strain data along the entire length of a pile can be performed with high reliability, which can be further processed to provide detailed information concerning pile behavior and load transfer properties [10]. These two types of DFOS technologies for measuring pile internal forces and deformation have the advantages of abundant monitoring information, high viability, easy implementation, accurate and reliable data, and good long-term stability.

This paper presents the basics of the DFOS-based pile monitoring system and introduces detailed sensor installation methods. Two case studies of using DFOS to measure pile strains during vertical and lateral loading are illustrated.

2 Fiber Optic Monitoring System of Piles

In order to effectively carry out pile testing, a distributed fiber optic monitoring system is developed. The framework of the monitoring system is shown in Fig. 1. The system is divided into four parts, including the measurement subsystem, the data acquisition subsystem, the data transmission and storage subsystem, and the data processing subsystem. As shown in Fig. 1, the stress and deformation characteristics of a pile are measured using fiber optic (FO) cables laid on the pile body. The data acquisition subsystem obtains the distributed information of temperature and strain of the pile shaft. Then, the data transmission subsystem connects the information to the network through the data transmission line and store the data in computers. Finally, the results of data processing and analysis are obtained in the data processing subsystem.

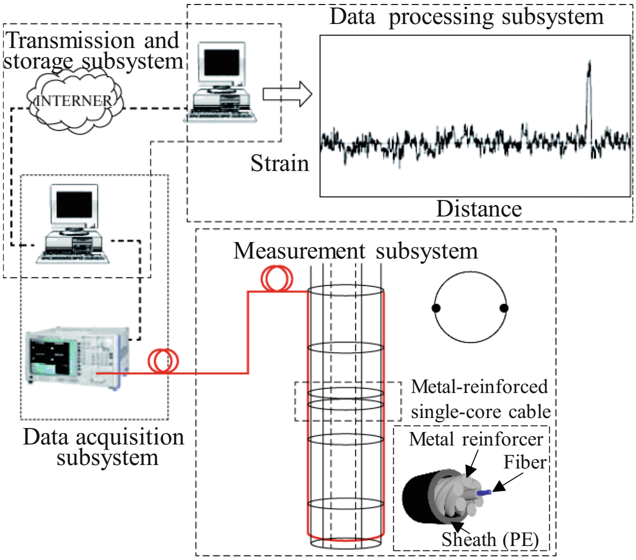

Fig. 1. Fiber optic monitoring system of piles

2.1 Measurement Subsystem

This subsystem comprises various sensors, including the distributed strain and temperature sensing cables, FBG strain sensors, FBG load cells, and FBG displacement sensors. The deformation compatibility between the FO cables and the pile body must be ensured so that the detected parameters can reflect the real state of the pile. If connections of FO cables are needed in the field, the optical fiber fusion splicer will be used. Using the distributed and long-distance monitoring characteristics of DFOS technologies, the monitoring data of multiple piles can be collected at one time, which greatly saves testing time.

2.2 Data Acquisition Subsystem and Data Transmission and Storage Subsystem

The subsystem comprises various optical fiber demodulation instruments and equipment, such as BOTDR, BOTDA, OFDR and FBG demodulators. During the test, the monitoring data of the sensing cables and FBG sensors under various loading conditions are obtained by the demodulation instrument. The collected data can be transmitted to the monitoring station automatically through the data transmission and storage subsystem. In general, the methods for data transmission are either wireless or wired.

2.3 Data Processing Subsystem

Unlike traditional point measurement technologies, the DFOS technology can obtain the distribution of strain and temperature along piles. The amount of monitoring data obtained in one test is tremendous. The DFOS-based pile performance evaluation system provides a powerful tool for the analysis and design of piles. The data processing subsystem mainly consider the following parts:

(a) Data read in section. This section mainly reads strain, temperature, wavelength, amplitude, time information, spatial positioning matching information and other relevant data from the database.
(b) Data processing part. Based on the strain, temperature, wavelength and other information obtained by the demodulator, pile strain and axial force, soil settlement around the pile, and pile skin friction caused by different soil layers on the pile side are calculated. At the same time, in data processing, some mathematical methods and means are used to revise the data, such as filtering, denoising, numerical integration and fitting. The wavelet analysis method is generally used for denoising, and the moving average method is used for smoothing.
(c) Output part. The output contents include strain curve, pile shaft axial force curve, friction value, $Q \sim s$ curve, $s \sim lgt$ curve.
(d) Diagnostic analysis. The maximum allowable deformation value of the pile shaft set in advance is used to identify abnormal points. Through identification, the relevant position information of abnormal points on the curve of strains and axial force is output in a specific way. According to these abnormal points, qualitative or quantitative analysis is made on the pile quality, pile deformation and damage mechanism.

3 Field Installation of Fiber Optic Sensors

Different types of piles have different working performance and load transfer mechanisms. Thus, the sensor installation and layout methods are quite different. In the following sections, the installation methods for precast piles, bored concrete piles and steel pipe piles are introduced.

3.1 Precast Pile

FO cables can be symmetrically embedded on two opposite sides along the axial direction of precast piles. In the process of slotting, firstly, it needs to determine the layout path of cables and mark it with an ink line. The cutting machine is used for slotting along the line. The recommended width of the groove is 2.0 mm–4.0 mm, and the depth of the groove may be 5.0 mm–8.0 mm. It passes through a U-shaped circuit at 50 cm from the pile bottom to ensure that the bending radius is greater than 100 mm. Use various tools such as a blower, brush and rag to remove dust from the groove and grind and straighten the uneven position in the groove.

Secondly, put the FO cable or FBG sensor into the design position in the groove after dispensing and fixing one end, properly pre-pull the fiber (e.g. 1000 $\mu\varepsilon$ in tensile strain), and then dispensing and fixing the other end. At the same time, it needs to glue the cable loop and set it in the slot. After the cable is implanted, the epoxy resin shall be coated, and the epoxy resin shall be repaired and leveled with a hot-air gun to ensure that all bubbles are eliminated. After 12 h, the epoxy resin glue is solidified, the other side of the pile shaft is constructed according to this method, and the bottom U-loop optical fiber is welded. Finally, the data transmission cable should be properly protected. The groove to embed the cables does not reach the pile top in most cases, so a suitable protection system should be provided to prevent the breakage of cables during pile pressing (Fig. 2).

Fig. 2. Layout of FO cables on a precast pile

3.2 Bored Pile

In order to monitor the pile behavior during pile load tests, it is necessary to ensure that the strain sensing cable is closely connected with the pile to make the deformation of the two consistent as much as possible. The quality of strain sensing FO cable determines the survival rate of the cable and affects the accuracy of monitoring results. Referring to the measuring principle of traditional reinforcement meters, the armored FO cables are laid on the two main reinforcements symmetrical to the reinforcement cage. The FO cables are fixed on the main reinforcement using the fixed-point bonding method, with a fixed point every 30–50 cm. In order to ensure that the sensing cables is laid vertically in a pile, a certain prestraining should be applied on the FO cables during fixation. The sensing cables laid in a pile are normally U-shaped. The laying position shall be close to the side of the main reinforcement of the reinforcement cage as far as possible to reduce the damage to the cable caused by concrete grouting. Then, the reinforcement cage with FO cables is inserted in the borehole, and then the concrete is poured in it slowly. In this way, the deformation of the cable is consistent with that of the pile. In order to prevent damage to the sensing optical cable during construction, the cables at the pile head should be specially protected (Fig. 3).

3.3 Steel Pipe Pile

For steel pipe piles, strain sensing FO cables with steel strands are generally installed on the steel pipe surface using welding and cementation. Then the pile is slowly driven into the soil layer. The installation of FO cables is divided into six steps: grinding in a pile, laying of FO cables, epoxy bonding, aluminum foil covering, channel steel covering, and pile head treatment, as shown in Fig. 4.

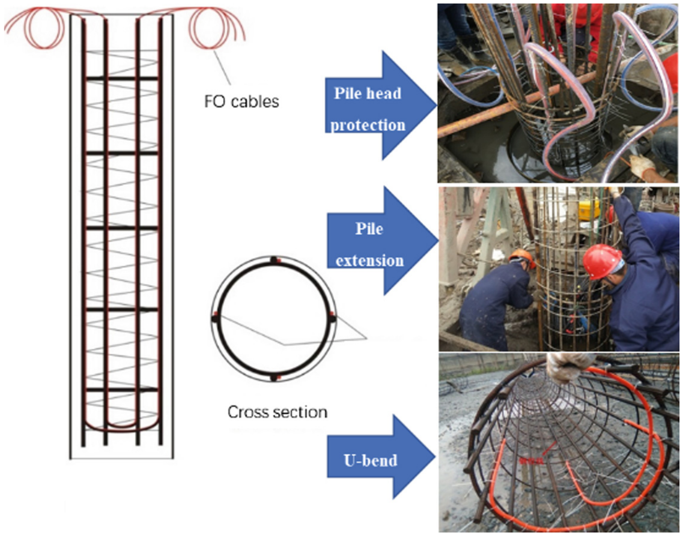

Fig. 3. Layout of FO cables on a bored pile

Fig. 4. Layout of FO cables on a steel pipe pile

4 Case Studies

4.1 Case Study 1: Vertical Static Load Test

The static load tests of a permeable pipe pile were performed in a construction site in Zhenjiang City, Jiangsu Province, China. The groundwater table was located about 2.0 m below the ground surface. The site is underlain consecutively with a plain fill layer, silty clay layer, silt layer and muddy, silty clay layer. The plain fill layer is mainly composed of silty clay, which is partially mixed with silt. The silt layer is locally composed of fine sand. The outer diameters and wall thickness of the test pile were 500 and 125 mm, respectively, and the pile length was 12 m. The bare FBG strain sensing arrays were installed for monitoring the axial strains of the test pile. Installation of the sensors is shown in Fig. 5. The FBG sensors were symmetrically embedded on two opposite sides of the test pile along the depth. Most FBG sensors were placed at 1.0 m intervals along the pile. The distance from the toe or the pile head to the nearest FBG sensors was 1.5 m to avoid the boundary effect. The static load tests were carried out in accord with the Chinese Code on Pile Testing.

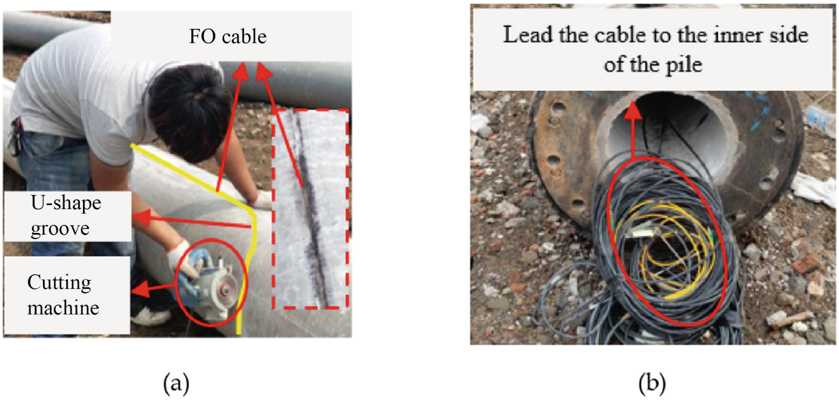

Fig. 5. Sensors installation in the field (adapted from [12]): (a) u-shape for installation of FBG sensors; (b) protection of fiber optical cables at the pile head.

The axial force profiles of the pile were calculated from strains multiplied by the pile axial rigidity, *EA*, and using $E = 3.8 \times 10^4$ N/mm^2. The value of E was obtained following the concrete strength of piles (C80). The axial force distribution curves of the permeable pipe pile in three static load tests are plotted in Fig. 6. It can be seen that the axial force increased steadily with the increase of load and gradually attenuated along the depth direction, showing an inverted triangle, which was the same as the distribution characteristics of the axial force of the pile shaft of a normal pipe pile. Because the pile side friction of each soil layer was different under the pile top load, the pile shaft axial force decreased nonlinearly along the depth. Under loading, the axial force changed significantly within 0–7 m of the pile shaft (miscellaneous fill, silty clay and silty soil layer), while the axial force transfer slowed down within 7–12 m (muddy, silty clay layer). The attenuation rate of axial force in the silt and silty clay layer was faster than that in the muddy, silty clay layer.

4.2 Case Study 2: Horizontal Static Load Test

At a construction site, a PHC pile with a diameter of 500 mm and a length of 15 m was built. In order to determine the deformation of pile top under free state horizontal load and determine the horizontal bearing capacity of the single pile, the horizontal loading test of the PHC pile was carried out, as shown in Fig. 7. In the test, FO cables were implanted in the PHC pile to couple it with the pile shaft for deformation, and the internal force and deformation of the pile shaft were measured. The pile top was sunk 40 cm below the ground, and the horizontal loading point was 1 m below the pile

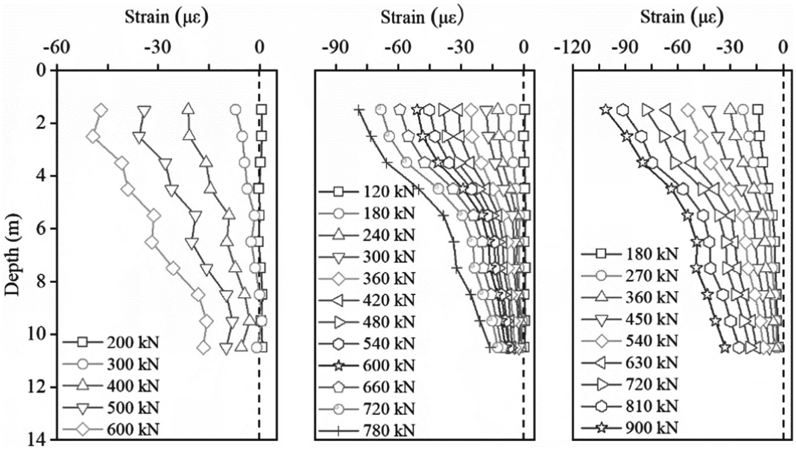

Fig. 6. Development of the pile axial strains with depth

top and 1.4 m below the ground. The horizontal hydraulic jack was used for applying horizontal loads in stages, 20 kN for each stage. A total of 11 steps were carried out. In the horizontal load test, the BOTDA optical fiber demodulator was used to collect strain data. According to the strain data, the deflection of the pile shaft was deduced and calculated.

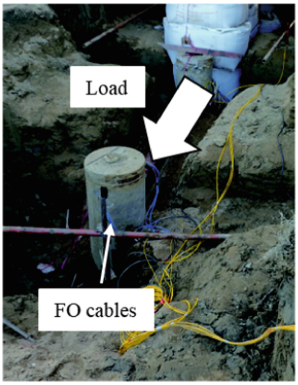

Fig. 7. Horizontal load test of a pile in the field

It can be seen from Fig. 8 that under the action of horizontal load, the displacement of the pile head increased with the increase of load. The zero point of pile displacement moves downward with the increase of load. It shows that the depth of the pile shaft affected by the horizontal load is increasing. The pile deflection changed obviously between 0–4 m. When the pile shaft was less than 4 m, the pile shaft deflection was small. The horizontal load mainly affected the soil in the upper 0–4 m. In this test, when the horizontal load reached the maximum horizontal load of 220 kN, the maximum influence

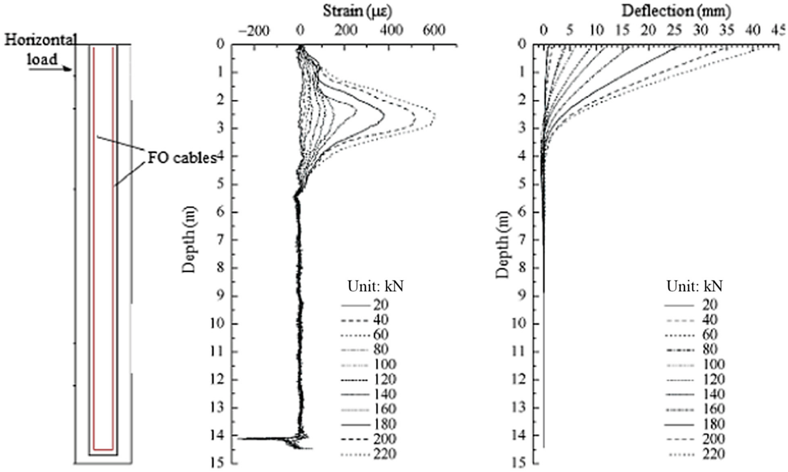

Fig. 8. Pile strains and deflection based on BOTDA

depth was about 6 m. The peak point (maximum strain point) of the pile strain curve increased with the increase of load, and the position of the peak point moved to the lower part of the pile. The results also show the superiority of BOTDA distributed monitoring, which can directly and accurately reflect the pile deformation and soil influence depth under horizontal load.

5 Conclusion

This paper presents the DFOS-based pile monitoring system and its field applications. The monitoring system is divided into four parts, including the measurement subsystem, data acquisition subsystem, data transmission and storage subsystem, and data processing subsystem. According to the construction characteristics of precast piles, bored concrete piles and steel pipe piles, various installation methods of FO cables or sensors are used. Two case studies are introduced to illustrate the performance of this pile monitoring system during vertical and horizontal static load tests. It proves that the distributed FO data can provide reliable information on the load transfer mechanism and bearing capacity. An available and reliable set of monitoring data along the whole pile length allows an estimation of the shaft friction development during testing, which is very important for optimizing pile design schemes.

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