Application of Fiber Bragg Grating Sensor in PHC Pipe Pile: Axial Force Test

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Abstract. According to special production processes of PHC pipe piles, the difficulties in monitoring them are clarified, and this problem can be solved by FBG sensors by virtue of their good performances. Based on the working principle of FBG, the calculation method of the pile under axial load is deduced. By means of engineering example, the processes of monitoring the axial force of the PHC piles by FBG sensors was introduced. The result shows that the installation methods and protective measures are feasible and can provide reference to similar projects. At the same time, the test data is analysed and the process of the axial force of the pile body is explained.

1. Introduction

Prestressed high strength concrete pipe pile (PHC pile), a new type of pile, due to outstanding performance, is widely used in various aspects of national construction [1]. PHC piles need to be prestressed, centrifuged and cured by high-temperature steam when they are manufactured. In the corresponding monitoring of PHC piles, the complicated production process of pipe piles makes the sensor face higher requirements. Meanwhile, the axial deformation is large when the piles are driven into the soil, which requires high resistance to deformation of the sensor. Due to the above-mentioned special requirements, the survival rate of the traditional resistance strain sensors is generally low when applied to concrete pipe piles in field test. Even if they survive, the sensors used are often difficult to meet test requirements in accuracy, drift, stability, and so on. In addition, traditional resistance strain sensors are more complex in construction. Therefore, it is necessary to find a sensing device that can meet the special requirements of PHC piles to carry out relevant field tests.

In recent years, optical fiber sensing technology has provided a new technology and means for engineering monitoring, among which the fiber Bragg grating (FBG) sensing technology is particularly prominent. Since Morey [2] first used the fiber grating as a sensor in 1989, FBG has been widely used in civil engineering, transportation, and energy by virtue of the advantages such as good electrical insulation, anti-electromagnetic interference, corrosion resistance, small size, small transmission loss, large transmission capacity, and wide measurement range [3]. At present, the development of fiber-optic sensor technology is becoming more and more mature, and the applications in various fields have shown a vigorous development trend, which is most likely to replace the
traditional sensor [4]. In this paper, the application of FBG in field test of PHC piles is explained based on the Maputo Bridge and Link Roads Project in Mozambique.

2. Principle of Fiber Bragg Grating sensor
Fiber Bragg Grating sensing technology is mainly used to encapsulate fiber gratings into a variety of different types of fiber grating sensors, deploying and installing them into the measured object, and measuring various deformation parameters of the measured object. Fiber Bragg Grating sensing technology can realize real-time online monitoring of wireless or wired automation [5].

FBG sensor is formed by changing the refractive index of the optical fiber core so that it produces a small periodic modulation. When the temperature or stress changes, the optical fiber produces axial strain [6]. The strain makes the grating period larger. At the same time, the optical fiber core and cladding radius become smaller, and the refractive index of the optical fiber is changed by the photoelastic effect, which causes the wavelength shift of the grating. Using the linear relationship between the strain and the wavelength shift of the grating, the measured structural strain is calculated.

![Figure 1. Principle of FBG Sensing System.](image)

As shown in figure 1, FBG is formed by the periodic change of the fiber core refractive index along the axial direction of the fiber. When the wavelength of the input signal and the period of FBG satisfy the condition of formula (1), the grating reflects the signal.

$$\lambda_B = 2n_{\text{eff}}\Lambda$$  

(1)

From formula (1), we can see that the reflected wavelength $\lambda_B$ is related to the grating period $\Lambda$ and the refractive index of the fiber $n_{\text{eff}}$. When the fiber is deformed axially or the temperature changes, the grating period and refractive index can be shifted, and the reflection wavelength is shifted accordingly. That is, by measuring the $\lambda_B$ drift, we can get the fiber deformation or temperature variation.

According to the experimental study [7], the strain and temperature both have a good linear relationship with the centre wavelength $\lambda_B$ and are independent of each other. The correlation formula is shown in formula (2).

$$\Delta\lambda_B = \alpha_\varepsilon \varepsilon + \alpha_T \Delta T$$  

(2)

where $\alpha_\varepsilon$ is the strain sensitivity coefficient of FBG, $\alpha_T$ is the temperature sensitivity coefficient of FBG, $\Delta T$ is the temperature variation, and $\varepsilon$ is the strain. Nowadays, the wavelength demodulation accuracy of FBG reaches 1 pm, the corresponding strain test accuracy is about 1 $\mu\varepsilon$, and the temperature demodulation accuracy is 0.1°C.
Under the action of the external load, the FBG sensor embedded in the pile is synchronously deformed with the PHC pile. In this way, the strain measured by the FBG sensor is that of the PHC pile. Based on the principle of material mechanics and the constitutive relationship of the pile, the axial force of the pile can be calculated by using the strain of the pile body.

3. Calculation of PHC pile under axial load based on FBG sensor

Axial compressive strain of the fiber is obtained by the instrument. Because the fiber is fixed in the PHC pile, the axial deformation of the fiber is consistent with the pile under axial load. Therefore, the compressive strain of the PHC pile is equal to that of the fiber.

The compressive stress of the pile $\sigma(Z)$ is:

$$\sigma(Z) = \varepsilon(Z) \cdot E_c$$  \hspace{1cm} (3)

where $E_c$ is the elastic modulus of the PHC pile.

The axial force of the pile $Q(Z)$ is:

$$Q(Z) = \sigma(Z) \cdot A$$  \hspace{1cm} (4)

where $A$ is the cross-sectional area of the PHC pile.

In this way, with the strain results tested by instrument, all the results can be obtained from formula (3) and (4). For the actual test project, there are two important parameters to be determined first: the elastic modulus $E_c$ and the cross-sectional area $A$ of the pile.

4. Project application

4.1. Project overview

The Maputo Bridge and Link Roads Project in Mozambique starts from the south bank of Maputo Bay and is linked to the proposed Maputo Bridge. The project area belongs to plain landform formed by sedimentary and alluvial sediments. After geological survey, the IK64+500~IK65+500 area is the development of soft soil in the floodplain of Maputo River. The prestressed concrete B-type pipe pile (PHC-B400) is designed to be used for treatment. The main parameters are as follows: pile diameter 0.4m, wall thickness 95mm, reinforcement ratio 0.99%, concrete compressive strength C80, pipe pile square arrangement, pile length 22m (two 11m piles welding), pile spacing 2.5m. The cross-sectional area $A$ of the tested pile is 0.091m$^2$, elastic modulus $E_c$ is $3.80 \times 10^8$MPa.

Figure 2. Layout diagram of FBG sensor. Figure 3. Location plan of FBG sensors in a pile.
The section IK65+310 is taken as the FBG sensor monitoring section. The total number of monitoring piles is 3 at this time. The FBG sensors are arranged with a sensing point at intervals of 2m. Two strings of fiber gratings are arranged for each pile, and their wavelengths are 1530, 1533.5, 1537, 1540.5, 1544, 1547.5, 1551, 1554.5, 1558, 1561.5, 1564. The specific installation points are shown in figure 2, 3 and 4.

As the pipe below the ground is affected by temperature, the FBG sensors in the axial force monitoring is also affected by temperature, and therefore it needs to be compensated for temperature. A fiber grating thermometer string is used to counteract the effects of temperature changes.

4.2. Installation process of FBG sensor

The steps for installing FBG are as follows:

(1) Draw the scheduled route on the pile.

Figure 5. Grooving on the surface of the pile.

Figure 6. Using a blower to clean the slotted body.

Figure 7. Inserting single-mode optical fiber along the slotted body.

Figure 8. Protecting by 5mm fiber-optic armored jacket tube.

Figure 9. Driving the pile.

Figure 10. Pile extension.
(2) A groove of about 5mm in depth and about 3mm in width is opened along the predetermined line outside the PHC pile (figure 5). The bottom position should be bent so that the fiber is not broken. Then use a blower to clean the slotted body (figure 6), especially to remove angular impurities.

(3) Insert 900μm diameter nylon jacketed single-mode tight-fitting optical fiber along the slotted body (figure 7) and insert a 5mm fiber-optic armored jacket tube at the end of the pile tip for protection (figure 8).

(4) While the fiber is implanted, the groove is sealed with epoxy resin and levelled using a heat gun. After 12 hours, the epoxy resin completely cured. Then flip the pile to complete the other side.

(5) Drive the first section of the pile (figure 9) and stop at about 0.5m from the pile head to ensure that there is enough space for the pile extension (figure 10). After welding is completed, epoxy resin is applied and the glass fiber cloth is wrapped to protect the splice fiber.

(6) Using 5mm sheathed wire, all monitoring lines are collected into the demodulator and data is recorded by connecting to a computer.

After installation of the FBG sensors, a portable demodulator is used for testing, and all sensors survived.

4.3. Testing data and analysis

The pile axial force measured by FBG sensors at a distance of 0.5 m from the top of the pile is taken as working load. Embankment is built at a rate of 0.3 m per week. With the embankment filling, the working load of three piles is gradually increasing. Moreover, working load is approximately linearly related to the surcharge load.

![Figure 11. Measured working load of three piles versus time.](image)

The curve of working load changing with embankment filling is shown in figure 11, where the working load of 1\textsuperscript{st} pile is the smallest and the working load of 3\textsuperscript{rd} pile is the largest. When starting filling, the axial force of three piles are almost equal. As the filling progresses, the overload increases. Due to the stress diffusion, the pile near the centre line of the embankment is more affected by the stress, so its growth rate is fastest and the additional stress is large. Similarly, the pile near the foot of the embankment is less affected, thus the stress increases slowly and the additional stress is small.

For 1\textsuperscript{st} pile, 2\textsuperscript{nd} pile, and 3\textsuperscript{rd} pile, the axial force of the piles at 21 days, 42 days, 63 days, 84 days, and 105 days are selected for analysis. As shown in Figure 12-14, the axial force of the pile body increases first and then decreases from top to bottom. The reason for this is mainly the effect of side friction resistance [8-9]. The property of side friction depends on the relative settlement of the pile and the soil around the pile. When the settlement at a certain point of the pile is greater than the settlement of the soil around, the positive frictional resistance will generate at that point, and vice versa.
Figure 12. Measured axial force of 1st pile versus depth.

Figure 13. Measured axial force of 2nd pile versus depth.

Figure 14. Measured axial force of 3rd pile versus depth.
Defining the maximum axial force as the neutral point, the pile body above the neutral point is subject to negative friction resistance. What is more, as the embankment filling load increases, the neutral point gradually moves upwards.

5. Conclusions
In this paper, FBG sensors are used to monitor the axial force of PHC pipe piles. The results show that:

(1) The survival rate of the FBG sensors in this test is 100%. The installation methods and protection measures adopted in this paper are feasible and can be used for similar engineering problems.

(2) With the embankment filling, the working load of three piles is gradually increasing, and working load is approximately linearly related to the surcharge load.

(3) The axial force of the pile near the centre of the embankment is greater than that of the pile body away from the centre.

(4) Due to the effect of side frictional resistance, the axial force of the pile body at each location is different. The direction of relative displacement between piles and soil determines the direction of frictional resistance.

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