Research on FBG Technology Applied in Highway Soft Foundation Pore Pressure Monitoring

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Abstract. The pore water pressure monitoring of soft ground pavement is one of the important technical links in highway construction monitoring. The use of traditional electrical measuring instruments to monitor pore water pressure has disadvantages such as low degree of automation, non-real-time data transmission, and high manual monitoring costs. However, fiber grating monitoring technology has developed rapidly due to its advantages of stable data transmission, convenient collection, and dynamic monitoring. Therefore, relying on the soft foundation pore water pressure monitoring project of Jiujiang Ring Expressway, the monitoring principle of the fiber grating seepage pressure sensor and the buried installation technology in the soft foundation are introduced. Through the long-term monitoring practice on the construction site, it is confirmed that the optical fiber monitoring system is applied to the soft foundation. The stability of base pore water pressure monitoring provides a reference for similar monitoring projects and engineering construction.

Keyword. Soft base monitoring, fiber Bragg grating, pore water pressure.

1. Introduction
The construction monitoring of soft base embankment has always been one of the key technical links in highway construction [1]. At present, the electrical method is mainly used in the soft foundation construction monitoring instrument. Although the traditional electric method instrument is low cost, it also has some deficiencies: it needs technicians to read and record the monitoring data point by point, which is time-consuming and laborious, and the data is influenced greatly by external interference. Sometimes the data drift is serious, which affecting the analysis results. In recent years, fiber Bragg grating monitoring technology has developed rapidly because of its strong resistance to external interference, high sensitivity and real-time transmission of monitoring data. Nowadays, fiber Bragg grating monitoring technology has been successfully applied in tunnels, slopes, dams, bridges and other engineering fields [2-8]. In the construction monitoring of soft foundation embankment, the application of this technology is still in its infancy because of the problems of monitoring object and sensor burying technology.

Based on the soft foundation construction monitoring project of Jiujiang highway around city, this paper introduces the monitoring principle of fiber Bragg grating seepage pressure sensor and the burying and installation method of sensor in embankment construction monitoring. It is proved by onsite monitoring practice that the pore water pressure monitoring of soft foundation embankment construction using optical fiber grating monitoring technology has the advantages of stable data and convenient data acquisition and etc. The purpose of this paper is to provide reference and guidance for the monitoring and construction of similar projects.
2. Basic Principle of Pore Water Pressure Monitoring based on FBG

The basic principle of fiber grating monitoring technology is to insert a grating into a small optical fiber by using a certain technology. The change of the specific period \( \Lambda \) of the grating and the effective refractive index \( n_{\text{eff}} \) of the fiber determine the change of the reflection or transmission wavelength \( \lambda_B \) of the transmitted light in the optical fiber. The relationship among them is as follows:

\[
\Delta \lambda_B = 2n_{\text{eff}} \Delta \Lambda
\]  

(1)

In the actual monitoring project, when the external strain displacement is transferred to the position of the grating, it will cause the change of the grating period \( \Lambda \) and the effective refractive index \( n_{\text{eff}} \). According to the relationship of (1), it will change the reflection center wavelength of the fiber grating inevitably, that’s to say, we can get the strain change data of the measured object by reading the change of the reflection center wavelength of the fiber grating through the instrument. At the position of the grating, the relationship between the strain \( \Delta \varepsilon \) and the reflection wavelength \( \lambda_B \) is as follows:

\[
\Delta \lambda_B = \lambda_B (1 - P_e) \Delta \varepsilon
\]  

(2)

In formula (2), \( P_e \) is the elastic-optic coefficient of the optical fiber.

According to the above principle, the change of grating reflection wavelength can be monitored by fiber Bragg grating demodulator, and the change of external strain parameters can fetched indirectly.

The structure diagram of the fiber Bragg grating osmotic pressure sensor is shown in figure 1 below.

Figure 1. Schematic diagram of FBG osmolality sensor.

In figure 1, the fiber grating is encapsulated in a stainless steel cylinder with a hole at the bottom. The stainless steel cylinder is filled with silicone rubber polymer to fix the fiber grating. The bottom of the stainless steel cylinder is a pervious stone. When the fiber grating osmotic pressure sensor is placed in a medium with pore water pressure, the pore water will enter the pressure chamber of the sensor through the pervious stone at the bottom of the sensor, and the stainless steel diaphragm will cause the compression of silicone rubber polymer on account of water pressure, which results in the axial stress and the axial strain of FBG. This strain can be expressed as:

\[
\Delta \varepsilon = \frac{\nu PA}{aE_{FBG} + \frac{L_{FBG}}{L_p} (A - a)E_{\text{polymer}}}
\]  

(3)

where \( A \) is the area of the disk and \( a \) is the cross-sectional area of the fiber grating, \( \nu \) is the Poisson's ratio of polymer, \( L_{FBG} \) is the length of fiber grating, \( L_p \) is the axial length of polymer, \( E_{FBG} \) and
respectively represent the elastic modulus of fiber grating and polymer, P is the external pressure.

From (2) and (3), it can be concluded that the relationship between the osmotic pressure and the reflection wavelength $\lambda_B$ of the grating is:

$$\Delta \lambda_B = (1 - P) \frac{\nu PA \lambda_B}{aE_{FBG} + L_{FBG} (A - a) E_{polymer}}$$

(4)

We set $k_p = (1 - P) \frac{\nu A}{aE_{FBG} + L_{FBG} (A - a) E_{polymer}}$. After simplifying formula (4), it can be concluded that:

$$\Delta \lambda_B = k_p P \lambda_B$$

(5)

where $k_p$ is the pressure coefficient of the FBG osmolality sensor.

It can be seen from formula (5) that the external pore water pressure can be obtained by monitoring the reflected wavelength data of the FBG osmotic pressure sensor, and the wavelength data of the sensor has a linear relationship with the pore water pressure in theory.

Figure 2 shows the calibration result of a FBG osmolality sensor.

![Figure 2](image_url)

**Figure 2.** Calibration results of FBG osmolality sensor.

3. Burying of Fiber Bragg Grating Osmotic Pressure Sensor

The main components of FBG osmometer sensor are made of corrosion-resistant stainless steel with high strength, which can be suitable for the extensive environmental conditions at the construction site, and can be directly buried in the embankment construction with high rolling degree. When the FBG osmometer sensor is buried at the site, it is necessary to drill holes at the buried position, the drilling depth should be about 25 cm below the monitoring position, and the hole should be cleared after the drilling completed, and backfill with fine sand with good water permeability at the bottom of the hole.
to the sensor end of the fiber grating osmometer. The osmometer can be in place, and then backfill the fine sand to 15 cm above the osmometer. Figure 3 is the schematic diagram of the on-site embedding of the fiber grating osmometer.

Figure 3. Schematic diagram of embedding of FBG osmolality sensor.

4. Monitoring and Analysis of Pore Water Pressure in Soft Foundation by Fiber Bragg Grating

4.1. General Situation of the Project

Jiujiang beltway is not only an important part of Jiangxi expressway network, especially the expressway network in northern Jiangxi, but also a key traffic construction project in the ecological economy zone around Poyang Lake in Jiangxi. The monitoring project is located in AK0+566-AK0+606 area, which is covered with 0.5m cultivated topsoil, generally 3.1-5.2 m thick yellowish brown plastic to hard plastic silty clay, with below From 12.5 to 20 meters thick, it flows from gray brown to soft plastic and soft plastic mucky clay, mainly in soft plastic shape, and gradually changes from flow plastic and soft plastic to soft plastic shape from top to bottom. The blow count of SPT is generally N = 34, local N = 67, underlying yellowish brown plastic to hard plastic silty clay.

The monitoring frequency is in accordance with the requirements of JTG/T3610-2019. During the construction period, the data shall be observed at least once for each layer of embankment filled, and at least once every three days when the embankment filling interval is more than 3 days; once every 15 days after the completion of embankment filling; due to the high automation of fiber Bragg grating sensor monitoring and on-site reading records The data is convenient. During the whole construction period of soft foundation filling and the consolidation period of soft foundation after filling (from March 2012 to January 2014), the storage data can be read according to the monitoring frequency even higher than the construction technical specifications.

4.2. Monitoring System Layout

The typical monitoring section selected for this embankment construction pore water pressure monitoring is located at AK0+586. Three boreholes are arranged in this section, which are respectively located at the center of the subgrade and the shoulders on both sides. The depth of the boreholes is 6 m below the original subgrade surface (level is+18.180). The fiber Bragg grating osmolality sensors placed in the three boreholes are labeled FBG1, FBG2 and FBG3 respectively. Figure 4 show the layout of section burying. The calibration results of three FBG osmometers are shown in table 1.

Figure 4. Layout of fiber grating monitoring section.
Table 1. Calibration results of FBG osmometer.

| Measuring point No | Central wavelength (nm) | Room temperature reading | Pressure coefficient (Kpa/nm) | Calibration coefficient R(%) |
|--------------------|-------------------------|---------------------------|------------------------------|-----------------------------|
| FBG1               | 1544.756                | 1528.380nm@20.3          | 848.166780                   | 99.99                       |
| FBG2               | 1540.955                | 1526.865nm@20.3          | 965.487007                   | 99.98                       |
| FBG3               | 1553.931                | 1532.033nm@20.3          | 991.113028                   | 99.99                       |

4.3. Monitoring Data Analysis

The monitoring data of pore water pressure of soft soil subgrade is shown in figure 5. From the time history curve of monitoring pore water pressure, it can be seen that the pore water pressure of the three monitoring points has increased in the first three months of embankment filling (from March 2012 to June 2012, about 100 days), which is related to rainfall in spring and summer and subgrade filling. In the following time, the pore water pressure of soft soil subgrade begins to dissipate, among which the consolidation process of the soil is obvious within three months (from 100 days to 200 days) after the completion of subgrade filling, and the change of pore water pressure in the later stage is slow. From the monitoring data, the consolidation process of the soft foundation can be dynamically understood. In the first three months after the completion of embankment filling, the consolidation process of the subgrade is obvious, and then the consolidation speed is slow down, which will last for one to two years or even longer.

According to the data comparison of the three monitoring points, the pore water pressure at the FBG2 measured point in the center of subgrade dissipates quickly. When the time reaches 600 days, the pore water pressure is 36.773 KPa, while at this time, the pore water pressure at the FBG1 and FBG3 monitoring points at the shoulder is 47.635 KPa and 42.711 KPa respectively. It shows that the consolidation speed of soft soil subgrade under the center of subgrade is faster than that at the shoulder.

5. Conclusion

(1) Through the long-time dynamic monitoring of soft foundation construction of Jiujiang beltway, the development law of soft foundation consolidation process is mastered, which provides a basis for construction process control and post-construction settlement prediction.

(2) Combined with the monitoring project of pore water pressure in soft foundation of beltway, this paper introduces the monitoring principle of fiber Bragg grating seepage pressure sensor and the
embedding and installation technology in soft foundation. Through the long-time monitoring of the construction site, it is proved that the stability of the optical fiber monitoring system is conducive to the dynamic monitoring of soft soil roadbed for a long time.

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