Development and Application of Fiber Bragg Grating Clinometer

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Abstract. Using FBG (fiber bragg grating) technology in clinometers can solve the technological problem facing by wireless transmission devices like big data transfer volume and poor stability, which has been receiving more and more attention. This paper discusses a new clinometer that is designed and transformed based on upgrading current clinometers, installing fiber grating strain gauges and fiber thermometers, and carrying out studies on such aspects as equipment upgrading, on-site setting, and data acquisition and analysis. In addition, it brings up the method of calculating displacement change based on wavelength change; this method is used in safety monitoring of the right side slope of Longyong Expressway ZK56+860 ~ ZK56+940 Section. Data shows that the device is operating well with a higher accuracy, and the slope is currently in a steady state. The equipment improvement and the method together provide reference data for safety analysis of the side slope.

1. Introduction
Slope clinometer is commonly used in engineering control. Traditional method is to use throw-in cable tester to measure the displacement number of clinometer tube[1], which is widely used. The advantage is mature technology and low cost while the disadvantage is that, the result is easy to be affected by climate and data acquisition is lagging. Monitoring technology has achieved a leapfrog development recently; GPS and optical fiber technology are used in slope monitoring[2]. GPS method has a wide application area. The advantage is easy data acquisition and can achieve remote operation; disadvantage is limited accuracy, instability, and high costs. While optical fiber technology, with the advantage of high accuracy, easy installation, and can achieve long-term long distance real time monitoring, has been using widely in geotechnical engineering. Comparing with other fiber optic sensors, FBG sensor has high sensitivity, and long service life. Optical grating with different pitch can be placed in the same optical fiber, to monitor temperature, stress, and strain at the same time[3,4]. It is feasible to combine FBG technology and traditional technology for measuring borehole deviation for which can both guarantee the accuracy of the data while achieving real time monitoring[5,6].

2 Designing and Installation of FBG Clinometer

2.1 Production of FBG Clinometer Sensor
The base material of the device is traditional PVC clinometer tube. Use slice-shaped FBG strainometer as monitoring element (element size is 1cm×6.5cm) and install it into the slide way, as graph 1[6], and group the element based on the wavelength shown on the element and the depth of each hole.
completing the installation inside each tube, put a temperature sensor to reduce the impact on wavelength detection caused by temperature variation; and using cable to connect each sensor.

2.2 Installation of the Clinometer

The drilling depth of clinometer hole is more than ten meters and has distinct diurnal temperature differences. Therefore, FBG temperature sensor should be installed in each hole to compensate the temperature\textsuperscript{[12,13]}. To connect 2 to 3 temperature sensors in series into displacement sensor system based on the length of the slope to compensate the temperature.

The detailed procedure of clinometer connecting installation is:

① Put a voltage-type liquidometer into the clinometer tube in the bottom, and pierce cable into clinometer tube one by one, so as to prevent liquidometer from failing to be put in the right place because there are too many cables in the tube after finishing pasting the strainometer;

② Traditional clinometer tube is placed and installed one by one. But because there are too many cables inside the device, more attention should be paid to protect the cable while installing; one person for each tube, and install at the same time.

③ Other steps are similar to the burial of traditional clinometer tube, which are: drilling (pore diameter of the drill is 10cm), down tube, discharging mud mixture by injecting water, sand filling in the hole, sealing and fixation. Binding all cables and numbering each tube after completing the burial.

![Figure 1. Installation Drawing of Clinometer](image)

3 FBG Signal Acquisition and Transmission

Signal acquisition is mainly divided into two processes: sensing and demodulation. Sensing is to modulate the parameter into the central wavelength of the sensor, and demodulation is to shift the reflected wave signal of the sensor into parameters. There are many methods to demodulate the signal, and this paper adopts modulable F-P filtering demodulation method. Considering the environment and condition of the slope are rather different during construction period and operating period, the signal acquisition and transmission plan is also divided into two modes; in construction period and in operating period.

3.1 The Acquisition and Transmission of Clinometer Signal during Construction Period

During the construction period, the slope has not been fully molded yet, and its reinforcement measure has not completed either. The platform has no conditions for laying cables and installing system and other perpetual transmission equipment. At this stage, the most commonly used way is manual data collection. The working process is as follows:
3.2 Signal Acquisition and Transmission during Operating period

During the operation period, the slope is comparatively stable and has conditions for laying long-term transmission equipment. Therefore, as for data collection, collection-demodulation-transmission method is adopted during operation period, namely, put a demodulator on the side of the slope, the wavelength signal of the sensor will then be demodulated into digital signal and transferred to the processing terminal in the slope maintenance institute.

4 Engineering Application

4.1 Project Overview

The height of the highest place in the right side slope of Longyong Expressway ZK56+860~ZK56+940 Section is 23 meters, which makes it a level 3 slope. It is mainly composed of clay and batt. The slope is located near the Danongche fault zone in Longshan County with broken rocks and poor stability. This FBG clinometer is buried in July 2014, and started monitoring since then. The direction inward the slope is defined as positive, and the outward the slope as negative.

4.2 Data Processing

FBG wavelength data cannot directly reflect the displacement situation of the slope; it can only reflect the change of grid pitch. It is necessary to do the conversion; to get the deflection of different point locations of the clinometer tube through strain calculation, and do the conversion to get slope displacement.

Using the difference method to calculate the deflection of the clinometer; the stress equation and stress-strain relation equation of FBG root position clinometer can be expressed as:

\[
\frac{1}{h^2} (f_{x+2h} - 2f_{x+h} + f_x) = \frac{1}{EI} \frac{MR}{R} = \frac{e_x}{R}
\]

(1)

The matrix expression is:

\[
\begin{bmatrix}
\frac{1}{h^2} & -2 & 1 & 0 & \cdots & 0 \\
0 & \ddots & \ddots & \ddots & \ddots & \ddots \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
\vdots & \ddots & \ddots & \ddots & \ddots & \ddots \\
0 & \cdots & \cdots & 0 & -2 & 1
\end{bmatrix}
\begin{bmatrix}
f_x \\
f_{x+h} \\
f_{x+2h} \\
\vdots \\
f_{x+(n-1)h}
\end{bmatrix} =
\begin{bmatrix}
\varepsilon_x \\
\varepsilon_{x+h} \\
\varepsilon_{x+2h} \\
\vdots \\
\varepsilon_{x+(n-1)h}
\end{bmatrix}
\]

(2)
In the matrix: \( \mathbf{A} \) and \( \mathbf{b} \) are deflections of the fixed end, \( n \) refers to the number of sensor, and the maximum in this research is 7 \( \mathbf{h} \) refers to the distance between two neighboring optical brag grating sensors, and in this research, the distance is 2m. \( R \) refers to the inner diameter of root position cable tester, and in this research, the specification of PVC clinometer tube is 0.58m. \( R \) refers to the strain value which is monitored by the \( i^{th} \) optical brag grating sensor counting from the bottom.

Assuming, and the bottom of the clinometer is buried under the rock stratum for 0.5m, which can be regarded as the fixed end. And are the deflection of the virtual point on the fixed end. Therefore, and we can get from the equation that:

\[
\begin{pmatrix}
1 & -2 & 1 & 0 & \cdots & 0 \\
0 & 1 & 0 & \cdots & \cdots \\
0 & 1 & -2 & \cdots & \cdots \\
\vdots & \vdots & \vdots & \vdots & \vdots \\
0 & \cdots & 0 & 1 & -2 & 1
\end{pmatrix}
\begin{pmatrix}
f_{2h} \\
f_{3h} \\
f_{(n+1)h}
\end{pmatrix}
= \begin{pmatrix}
e_1 \\
e_2 \\
\vdots \\
e_n
\end{pmatrix}
\tag{3}
\]

In formula 3, the first and second column of the matrix can be neglected, and the equation can be simplified as:

\[
\begin{pmatrix}
1 & 0 & 0 & 0 & \cdots & 0 \\
-2 & 1 & 0 & \cdots & \cdots \\
1 & -2 & \cdots & \cdots & \cdots \\
0 & 1 & -2 & \cdots & \cdots \\
0 & \cdots & 0 & 1 & -2 & 1
\end{pmatrix}
\begin{pmatrix}
f_{2h} \\
f_{3h} \\
f_{(n+1)h}
\end{pmatrix}
= \begin{pmatrix}
e_1 \\
e_2 \\
\vdots \\
e_n
\end{pmatrix}
\tag{4}
\]

The above matrix is reversible. By finding the inverse matrix, one can figure out the relation between displacement and the strain of the measuring point. As follows:

\[
\begin{pmatrix}
f_{2h} \\
f_{3h} \\
f_{(n+1)h}
\end{pmatrix}
= \frac{h^2}{R}
\begin{pmatrix}
1 & 0 & 0 & \cdots & 0 \\
-2 & 1 & 0 & \cdots & \cdots \\
1 & -2 & \cdots & \cdots & \cdots \\
0 & 1 & -2 & \cdots & \cdots \\
0 & \cdots & 0 & 1 & -2 & 1
\end{pmatrix}^{-1}
\begin{pmatrix}
e_1 \\
e_2 \\
\vdots \\
e_n
\end{pmatrix}
\tag{5}
\]

That is:

\[
\begin{pmatrix}
f_{2h} \\
f_{3h} \\
f_{(n+1)h}
\end{pmatrix}
= \frac{h^2}{R}
\begin{pmatrix}
1 & 0 & 0 & \cdots & 0 \\
2 & 1 & 0 & \cdots & \cdots \\
3 & 2 & 1 & 0 & \cdots \\
4 & 3 & 2 & \cdots & \cdots \\
n & n-1 & \cdots & 4 & 3 & 2 & 1
\end{pmatrix}
\begin{pmatrix}
e_1 \\
e_2 \\
\vdots \\
e_n
\end{pmatrix}
\tag{6}
\]

This shows that, by model simplification and assuming the clinometer, one can establish the relation between strain and displacement. In formula 6, except the strain value, which is acquired by calculating the data collected from FBG demodulator, the rest are constant. Therefore, the treating method of the data can also be used as the computing method of the data collected by the device.

4.3 Displacement Analysis

By analyzing above equation one can get relevant data of this slope, and after processing, one can get its displacement-time graph. As shown below:
Figure 4. Displacement-time Changing Curve

The displacement-depth curves of each measured holes are V-shaped, and the upper displacement is larger and the lower displacement is smaller. The curves of 1# and 4# holes have obvious convex points at the position 3~4m below the platform, which shows that the upper displacement, which is more than 3m, of the above two holes is larger than that of the lower displacement. The maximum monthly average displacement of the single hole of the slope is 15~17mm, which is located in 2# and 3# holes which are at the end of two sides of the slope, and the #1 and 4# holes in the middle of the slope have smaller accumulative displacement change. According to the data and data processing method of the new device, the displacement curve is basically the same as the slope displacement trend, the accuracy of the measured data is higher than that of the traditional device, and the performance is improved obviously.

5 Conclusion

(1)This paper introduced the design, transform, inbuilt, signal transmission and data processing method of a clinometer, which is based on FBG technology. It offers new plan for monitoring the stability of the slope, and has obvious popularization using value.
(2) By monitoring the right side of Longyong Expressway ZK56+860 ~ ZK56+940 Section, the clinometer provides data reference for maintenance management in operating period. Comparing with traditional clinometer, the new one is more accurate, convenient in data collection; and it can get more data.

Reference

[1] Ma Quanzhen, Zhang Baohua, Application of Borehole Clinometer in Slope Monitoring[J]. Journal of Changzhou Institute of Technology, 2005(S1).
[2] Shen Qiang, Study on Monitoring and Prediction of Layered Rock Slope Stability of Highway in Mountainous Region[D]. Graduate University of the Chinese Academy of Sciences, Wuhan Institute of Rock and Soil Mechanics, 2007.
[3] Sui Haibo, Shi Bin, Zhang Dan, Wang Baojun, Wei Guangqing, Piao Chunde, REVIEW ON FIBER OPTIC SENSOR-BASED MONITORING TECHNIQUES FOR GEOLOGICAL AND GEOTECHNICAL ENGINEERING[J]. Journal of Engineering Geology, 2008(01).
[4] Song Zhen, Wang Baojun, Shi Bin, Zhang Dan, Sui Haibo, Li Haitao, Comparative Analysis of Fiber Monitoring and Numerical Simulation on the K3 Slope of Guangdong-Jiangxi Expressway[J]. Journal of Disaster Prevention and Mitigation Engineering, 2009(04).
[5] Sui Haibo, Shi Bin, Zhang Dan, Wang Baojun, Wei Guangqing, Piao Chunde, STUDY ON DISTRIBUTED OPTICAL FIBER SENSOR-BASED MONITORING FOR SLOPE ENGINEERING[J]. Chinese Journal of Rock Mechanics and Engineering, 2008(S2).
[6] Pei Huafu, Yin Jianhua, Zhu Honghu, Hong Chengyu, Fan Youhua, IN-SITU MONITORING OF DISPLACEMENTS AND STABILITY EVALUATION OF SLOPE BASED ON FIBER BRAGG GRATING SENSING TECHNOLOGY[J]. Chinese Journal of Rock Mechanics and Engineering, 2010(08).
[7] Peng Bei, Meng Lijun, Research and Development on Distributed Fiber Bragg Grating Sensors[J]. Software Guide, 2012(06).
[8] Yang Xing, Hu Jianming, Dai Teli, Principle and Typical Current Applications of Fiber Grating Sensors[J]. Journal of Chongqing Normal University(Natural Science), 2009(04).
[9] Pang Dandan, Investigation on the Novel Fiber Bragg Grating Sensing Technology[D]. Shandong University, 2014.
[10] Zhu Honghu, Yin Jianhua, Jin Wei, Gu Dongming, Health monitoring of foundations using fiber Bragg grating sensing technology[J]. China Civil Engineering Journal, 2010(06).
[11] Chen Pengchao, Li Jun, Liu Jianping, Jin Shijiu, Monitoring technology of pipelines using fiber bragg grating and its application in landslide areas[J]. Chinese Journal of Geotechnical Engineering, 2010(06).
[12] Hu Zhixin, Wang Zhenwu, Ma Yunbin, Zhang Jun, Soil pressure sensor based on temperature compensation FBG[J]. Journal of Applied Optics, 2010(01).
[13] Zhao Tao, Monitoring Principle and Method of Transformer Internal Temperature Based on the FBG Temperature Sensing[D]. Chongqing University, 2008.
[14] Yao Hongxu, Wei Bingxu, Qualitative analysis and estimation of inclination survey data curve in slope slip monitoring[J]. Engineering Construction, 2011(03).