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Regular Articles

Experimental study on an FBG strain sensor

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ABSTRACT

Landslides and other geological disasters occur frequently and often cause high financial and humanitarian cost. The real-time, early-warning monitoring of landslides has important significance in reducing casualties and property losses. In this paper, by taking the high initial precision and high sensitivity advantage of FBG, an FBG strain sensor is designed combining FBGs with inclinometer. The sensor was regarded as a cantilever beam with one end fixed. According to the anisotropic material properties of the inclinometer, a theoretical formula between the FBG wavelength and the deflection of the sensor was established using the elastic mechanics principle. Accuracy of the formula established had been verified through laboratory calibration testing and model slope monitoring experiments. The displacement of landslide could be calculated by the established theoretical formula using the changing values of FBG central wavelength obtained by the demodulation instrument remotely. Results showed that the maximum error at different heights was 9.09%; the average of the maximum error was 6.35%, and its corresponding variance was 2.12; the minimum error was 4.18%; the average of the minimum error was 5.99%, and its corresponding variance was 0.50. The maximum error of the theoretical and the measured displacement decrease gradually, and the variance of the error also decreases gradually. This indicates that the theoretical results are more and more reliable. It also shows that the sensor and the theoretical formula established in this paper can be used for remote, real-time, high precision and early warning monitoring of the slope.

1. Introduction

China has some of the most serious geological disasters in the world. According to the statistics of the Chinese Institute of Geological Environment Monitoring [1], in the last ten years, landslides and other disasters caused by slope instability in China led to a direct economic loss of RMB 45.6 billion Yuan and 11230 casualties, which has seriously affected people's lives and property safety. The real-time and early-warning monitoring of landslides has important significances in reducing casualties and property losses.

There are many landslide monitoring methods. Macroscopic geological monitoring methods and station observation methods can determine the slope deformation scope, with a wide monitoring range. However, these methods are labor intensive, easily affected by the weather, and unable to realize real-time distributed monitoring. By contrast, Global Position System (GPS) and Remote Sensing (RS) methods can realize remote monitoring. However, these methods can only observe the surface deformation of the slope, and cannot acquire the deformation inside the soil body [2,3].

Deep displacement monitoring methods, based on slope drilling, are becoming widely used, since they can monitor the deep displacement of slope, obtain the position of the slip plane and estimate the volume of the landslide. Inclinometer [4,5] is relatively accurate, but the real-time performance and the telemetry effect are poor. Time Domain Reflectometry (TDR) [6,7], based on a coaxial cable, can realize real-time telemetry at a lower cost, with shorter data acquisition time and higher safety. However, the initial accuracy is poor, and measurement range is not large. Therefore, it cannot be used for areas without shear action, and it cannot determine the direction of the landslide. Tang et al. [8] carried out experiments by burying single fibers in a concrete cylinder, showing the feasibility of optical fibers in the application of slope monitoring as a sensing element. Single fibers are, however, liable to brittle fracture and not easy to pave. Their initial precision can reach 0.3 mm, but their measuring range is only 3.6 mm. Brillouin Optical Time Domain Reflectometry (BOTDR) [9], based on Brillouin scattering, can realize remotely and real-time distributed telemetry, but the light intensity is weak and the line width is narrow. Fiber type, fiber laying and other key problems need to be solved. When the temperature

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difference is large, the Brillouin frequency will drift significantly. Brillouin Optical Time Domain Analysis (BOTDA) [10,11] has a strong light signal, and can realize real-time distributed monitoring. But since BOTDA needs incident laser from both ends of the optical fiber, it makes monitoring inconvenient. The monitoring system is costly and cannot measure the breakpoint.

Fiber Bragg Grating (FBG) has the advantages of high measuring precision, strong instantaneity, a wide measuring range and anti-electromagnetic interference, which all make it suitable for high speed and high precision real-time monitoring. Some researchers [12–16] have used FBG joint inclinometer for landslide monitoring. These researches had shown that the FBG sensor has good sensitivity and reliability. Based on the beam bending theory and difference algorithm, the relation between each point displacement of in-place inclinometer and the point strain measured by the sensor is derived. Based on the beam element decomposition and material mechanics principle, the relation between the change of grating signal and the displacement is derived. However, they have not taken the inclinometer was anisotropic material into account, nor have they taken FBG and inclinometer as a sensor to study or established landslide prediction formulas.

Based on the previous research of our team, an FBG strain sensor is designed. The sensor is regarded as a cantilever beam with one end fixed. Considering the anisotropic material properties of the inclinometer, the theoretical formula of the optical grating central wavelength and the sensor deflection is established by using the elastic mechanics principle. The accuracy of the relation has been verified through laboratory calibration testing and model slope monitoring experiments. By using this formula, the slippage of the slip plane can be obtained remotely and in real time. The high-precision, high-sensitivity, remote, real-time and early-warning monitoring is then realized.

2. Slope monitoring technology based on FBG strain sensor

2.1. Strain sensing principle of the FBG

An FBG takes advantage of the photosensitivity of the fiber, and forms a spatial phase grating in the fiber core. This is equivalent to a narrow-band filter or reflector. When a wide spectrum of light is incident, the wavelength meeting FBG Bragg condition will be reflected, and all other wavelengths will be transmitted through the FBG.

The central wavelength λ_B [17] of the FBG satisfies the following equation:

$$\lambda_B = 2\eta_{eff}\Lambda \tag{1}$$

where η_{eff} is the effective refractive index and Λ is the grating period.

When temperature, stress, strain or other physical parameters of the FBG environment change, the period or fiber core refractive index of the optical grating will also change, and this leads to a change in the wavelength of the reflected light. The optical grating central wavelength change caused by strain and temperature can be expressed as [18].

$$\begin{aligned}\Delta\lambda_B &= 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial l} + \eta_{eff}\frac{\partial\Lambda}{\partial l}\right)\Delta l + 2\left(\Lambda\frac{\partial\eta_{eff}}{\partial T} + \eta_{eff}\frac{\partial\Lambda}{\partial T}\right)\Delta T\\ &= 2\eta_{eff}\Lambda\left(\left\{1-\left(\frac{\eta_{eff}^2}{2}\right)[P_{12}-\nu(P_{11}+P_{12})]\right\}\varepsilon + \left[\alpha_f + \frac{\frac{d\eta_{eff}}{dT}}{\eta_{eff}}\right]\Delta T\right)\\ &= \lambda_B(K_T\Delta T + K_\varepsilon\varepsilon)\end{aligned} \tag{2}$$

where P_{11} and P_{12} are photo-elastic coefficients of the FBG; ν is the optical fiber Poisson ratio; is the strain sensitivity of the FBG, of which, $K_\varepsilon = \frac{\Delta\lambda_B}{\lambda_B}\Big/\Delta\varepsilon = 1-P_e$, $P_e = \left(\frac{\eta_{eff}^2}{2}\right)[P_{12}-\nu(P_{11}+P_{12})]$, P_e is the fiber effective photo-elastic coefficient. For a germanium doped silica fiber $P_e = 0.22$. K_T is the temperature sensitivity of the FBG, $K_T = \frac{\Delta\lambda_B}{\lambda_B}\Big/\Delta T = \alpha_f + \xi$, α_f is fiber coefficient of thermal expansion and ξ is the thermos-optical coefficient.

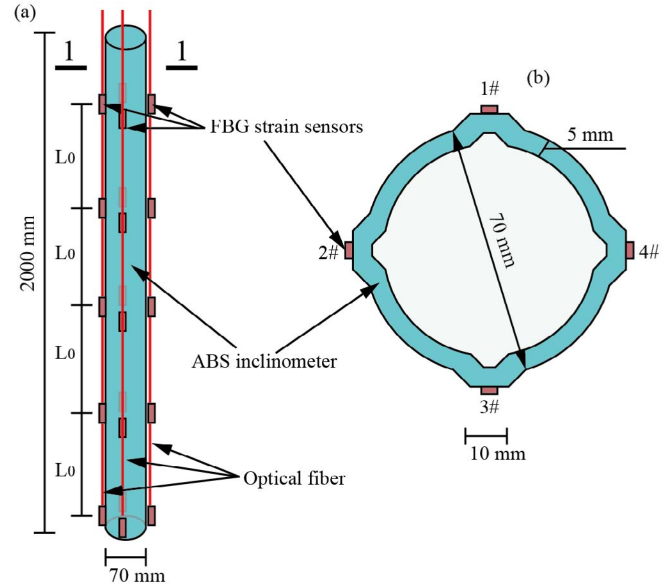

Fig. 1. Schematic diagram of FBG strain sensor (a) Elevation (b) 1–1.

When the temperature is constant, the relationship between the change of the optical grating central wavelength and the strain is as follows:

$$\frac{\Delta\lambda_B}{\lambda_B} = (1-P_e)\varepsilon = K_\varepsilon\cdot\varepsilon \tag{3}$$

2.2. Design of the grating FBG strain sensor

The FBG strain sensor reported in this paper takes the inclinometer as the load bearing surface and the FBG carrier. Four guide grooves are evenly distributed on the ABS tube, the maximum outer diameter of the inclinometer is 70 mm, the tube wall is 5 mm thick, the groove bottom distance of opposite sides is 65 mm, the guide groove is 3 mm deep, and each section is 2 m long. The FBG, arranged and numbered according to Fig. 1, is glued around the ABS inclinometer. The layout spacing L_0 can be set as needed, for example 25 cm, 50 cm, 100 cm, etc. The length of the sensor can be increased by connection of several inclinometers. The FBG strain sensor is shown in Fig. 1.

2.3. Implementation of slope monitoring based on FBG strain sensor

To implement slope monitoring, the following steps are required. Firstly, according to the monitoring needs and the actual situation of the slope, select the monitoring position, drill a hole with diameter not less than 110 mm which goes through the slip plane and reaches the stable rock or soil layer. Secondly, insert a PVC pipe with a diameter of 110 mm into the borehole immediately after it is formed so as to avoid collapse of the hole. Finally, place the FBG strain sensor in the borehole, pour cement mortar with ratio of 1:5 using pressurization from the bottom of the hole while removing the PVC tube at the same time until the borehole is filled. Monitoring can begin after the grouting taking approximately three days curing.

Because the FBG strain sensor is strongly interfaced with the measured slope through the grouting material, it is subject to common deformation with surrounding rock and soil mass.

When the installation is completed, if the measured slope slides, its displacement will cause deformation of the sensor and the FBG output signal will change. The output signal is collected and demodulated by the demodulator and the monitoring of the deep displacement of the