Landslide Monitoring Based on High-Resolution Distributed Fiber Optic Stress Sensor

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Abstract—A landslide monitoring application is presented by using a high-resolution distributed fiber optic stress sensor. The sensor is used to monitor the intra-stress distribution and variations in landslide bodies, and can be used for the early warning of the occurrence of the landslides. The principle of distributed fiber optic stress sensing and the intra-stress monitoring method for landslides are described in detail. By measuring the distributed polarization mode coupling in the polarization-maintaining fiber, the distributed fiber stress sensor with stress measuring range 0 to 15 MPa, spatial resolution 10 cm and measuring range 0.5 km, is designed. The warning system is also investigated experimentally in the field trial.

Index Terms—Distributed fiber optic stress sensor, landslides, warning monitoring system.

1. Introduction

Landslide is one of the most costly catastrophic events in terms of human lives and infrastructure damage, early warning monitoring for landslides becomes more and more important. Especially, the monitoring for landslides in man-made structures, such as bridges, dams and hydraulic engineering, plays a key role in the prevention and mitigation of risks related to natural and technological hazards. In most cases the occurrence of landslides is originated by the loss in equilibrium of the soil mass due to changes in one or more parameters, such as seismic noise, ground displacements, piezometric level and rainfall, which contribute to leaving the mass itself stable. Through continuous monitoring the correlation parameters, the dynamics activity of the landslide can be observed. In the past twenty years, many monitoring methods were proposed, but the dominant method is displacement amount testing, such as mechanics-electronics displacement measuring, topographic surveys and GPS surveys\textsuperscript{[1]-[2]}. These traditional monitoring techniques give information about displacements only in a few numbers of points. In addition, it takes much time and money for a large number of points to measure on a continuous basis. In fact, the landslide will occur when the balance between the hill’s weight and the countering resistance forces is tipped in favor of gravity. So, if the intra-stress distribution and changes of the landslide bodies can be monitored, the occurrence of landslides will be predicted accurately. With particular advantage, a distributed fiber optic stress sensor can be used to monitor the intra-stress distribution and changes in landslide bodies. According to the characteristics of the intra-stress distribution and changes detected by the distributed fiber optic stress sensor, combining with some applications of specific mathematical models, the movement the landslides can be predicted, thus the disaster can be avoided.

The distributed fiber optic stress sensor permits the measurement of a desired parameter as a function of the length along the optical fiber. With particular advantage for the applications in long continuous space testing, many techniques have been developed, such as POTDR, OFDR, BOTDR, ROTDR, etc. Recently, a novel distributed fiber optic stress sensor based on polarization coupling coherence attracts the attention, due to combination of absolute measurement with high-resolution, high sensitivity and large dynamic range\textsuperscript{[3]-[7]}. It has been proved that polarization mode coupling within a polarization-maintaining fiber (PMF) induced by an external force could be used to measure stress on the fiber.

In this paper, we present an early warning monitoring method to predict the occurrence of landslides, using a distributed fiber stress sensor based on polarization coupling coherence to monitor the intra-stress distribution and changes. According to the requirements for the application in landslides monitoring, a distributed fiber stress sensor with stress measuring range 0 MPa to 15 MPa, spatial resolution 10 cm and measuring range 0.5 km, was designed. The presented warning system was investigated in the field trial in the Three Gorges mountain area.
2. Operation Principle

2.1 Distributed Fiber Optic Stress Sensor and Warning System Configuration

The detailed structure of the distributed fiber stress sensor used in warning system is designed as Fig. 1. It was formed by a superluminescent diode (SLD) operating at 1310 nm, a section polarization-maintaining fiber (PMF) under test, Michelson interferometer and signal processor. As broadband source, the SLD emits linear-polarization light through a section PMF acted as pig-tailed. So the SLD and PMF under test can be perfectly fused together with minimal connect losses. The Michelson interferometer used in the system compensates an optical path difference (OPD) between the two spatially separated polarization light beam that cause in PMF under test to recover the path length imbalance and then create interference condition. The Michelson interferometer consists of a scanning arm driven by a stepping electric motor and a fixed arm.

When the linear-polarization light propagates along the PMF, the polarization coupling occurs at the point where the fiber encounters environmental and mechanical perturbation, such as pressure, temperature and twist. The coupling mode ejected from the end of the PMF is split into two beams at the beam splitter (BS). One beam is reflected by mirror1 \( M_1 \) acted as the fixed arm of the Michelson interferometer. The other beam is reflected by mirror2 \( M_2 \) acted as the scanning arm of the Michelson interferometer. Then the two beams reflected by \( M_1 \) and \( M_2 \) are transmitted to the polarizer and the two light beams interfere with each other. The interference optical signal is focused and detected by a high-sensitivity and low-noise PIN-FET module. At last, through the signal processor and computer, the position and intensity of the distributed polarization mode coupling are calculated, namely the position and magnitude of the external force can be realized absolute measurement.

If the intra-stress in landslide bodies is modulated onto PMF with a specific stress modulator, the distribution and changes of the intra-stress can be measured. The distribution and changes of intra-stress acting on modulators. The specific stress modulator configuration is pictured in Fig. 3 (b)[7]. A mobile plate and a static plate constitute the periodic tooth-shaped modulator structure, and a PMF under test is put between the mobile plate and static plate. The mobile plate is fixed on the center of the elastic diaphragm and the static plate is welded on stiff case. When intra-stress acts on the elastic diaphragm to occur the strain, the mobile plate will move and then press the PMF.

![Fig. 1. The distributed fiber stress sensor configuration.](image1)

![Fig. 2. Intra-stress monitoring method.](image2)

![Fig. 3. System configuration: (a) Stress modulator installing method and (b) The structure of stress modulator.](image3)

2.2 Polarization Mode Coupling Sensing Theory and Warning Monitoring Method

The PMF has two preferred birefringence axes. When a linear polarization light injects into the PMF at the field components \( \text{HE}_{11x} \) direction and an external force applied to a random point of the PMF, part of \( \text{HE}_{11x} \) mode will couple into \( \text{HE}_{11y} \) at this point position. When \( \text{HE}_{11x} \) mode...
and HE_{11y} mode propagate distance \( L \), a group velocities delay difference \( \tau_1 \) occurs. But when the HE_{11x} and HE_{11y} mode propagate in the interferometer, a new delay difference \( \tau_2 \) would be obtained by adjusting the scanning arm. The \( \tau_1 \) and \( \tau_2 \) can be expressed as[3]:

\[
\tau_1 = \left( \frac{d\beta_x}{d\omega} - \frac{d\beta_y}{d\omega} \right) L, \quad \tau_2 = \frac{\Delta L}{c}
\]

where \( \beta_x \) and \( \beta_y \) are the propagation constants of the HE_{11x} and HE_{11y} mode, \( \Delta L \) is optical path difference of the Michelson interferometer, \( c \) is the light velocities. So the total delay would be gained by the formula \( \tau = \tau_1 - \tau_2 \).

When \( \tau_1 > \tau_2 \) ( \( \tau_2 \) is the coherent time of the light source), the interference between the HE_{11x} and HE_{11y} mode could not be obtained. But if by adjusting the optical path difference in interferometer, \( \tau < \tau_2 \), the interference between the HE_{11x} and HE_{11y} mode would occur. The intensity of the coherent optical power denotes the magnitude of the external force. So, through changing the \( \Delta L \) by continuous adjusting the scanning arm of the Michelson interferometer, the external force along the PMF under test would be measured, namely distributed sensing. The position suffering external force and the spatial resolution are calculated through the following formula[3]:

\[
z = \frac{\Delta L}{B}, \quad R = \frac{L_x}{B}
\]

where \( B \) is the modal birefringence of the PMF, \( L_x \) is the coherent length of the optical source.

In any cases, the occurrence of landslides goes together with continuous soil movements, the intra-stress in landslide bodies change too. The early warning monitoring system is designed according to Fig. 2 and Fig. 3. It acquires data about intra-stress distribution and changes of landslide bodies periodically, builds up a database of the stress distribution and changes along with time. By means of the relation curve of stress-time, combining with some applications of specific mathematical models, the occurrence of landslides could be forecasted accurately.

3. Experimental Results and Analysis

The key component in the warning monitoring system is the distributed fiber optic stress sensor based on polarization mode coupling, which collects data about the intra-stress distribution and changes of landslide bodies. According to the requirements for intra-stress monitoring, the distributed fiber stress sensor is designed. Because the measuring depth for landslide bodies ranges from several decade meters to few hundred meters, a 0.5 km length PMF with beat length (\( L_b \)) 3.0 used in experiment system and the scanning length of the scanning arm must exceed 100 mm. The spectral bandwidth and output power of the SLD used are 40 nm and 2 mW respectively. Synthesizing the influence from \( L_x \), \( L_y \), and shifting precision of the scanning arm, less 10 cm spatial resolutions can be obtained in this distributed sensor. If the fixed arm is well adjusted by a Piezo-electronic transducer (PZT), the spatial resolutions would improve more[6]. It is well known that maximum coupling occurs when the force is applied 45 degrees to the birefringence axes, so a specific stress modulator used in this sensor to avoid this limit[7]. Since the Stress is modulated to PMF by the modulator, the stress measuring range is determined by the thickness of the elastic diaphragm. Through designing the thickness of diaphragm, we can ensure the stress measuring range 0 MPa to 15 MPa.

![Fig. 4. Curve of intra-stress, water level and rainfall changing along with time.](image)

To prove the validity of the method through monitoring intra-stress distribution and changes of the landslide bodies, the field trial has been implemented in Three Gorges Project. At the same time, two traditional monitoring methods, namely water lever monitoring and rainfall monitoring, have been carried out also. The corresponding experimental result is shown in Fig. 4. From the experimental conclusions, the intra-stress monitoring keeps very identical result to the water lever and rainfall monitoring. So the intra-stress monitoring method based on the distributed fiber optic stress sensor presented in this paper is very effective to forecast the occurrence of the landslides. At the same time, the sensor system receives the sensing signal, digitizes and stores them in specific files, and permits their download by means of computer storage media. The computer in the system can select anyone sensor array to test by an optical switch. By means of GPRS module, each sensor transmits monitoring data to the remote control center, thus sensor network system for landslide monitoring is constructed.

4. Conclusions

A high performance early warning monitoring method for landslides based on distributed fiber optic stress sensing
and intra-stress monitoring is presented. This method utilized the distribution and changes of intra-stress in landslide bodies to predict the landslide disasters. The high-resolution distributed fiber stress sensor based on polarization coupling coherence with stress measuring range 0 MPa to 15 MPa, spatial resolution 10 cm and measuring range 0.5 km, is designed. Using the specific stress modulator, the distribution and changes of the intra-stress in landslide bodies is measured accurately. According to the experimental result from the field trial in Three Gorges Project, this warning monitoring method is very effective. Since the proposed method has many advantages in terms of high spatial resolution, high-sensitivity, easy networking to monitor landslides in a large area, it can also be used to monitor the engineering disasters in bridge, hydraulic engineering and architecture.

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References


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