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# A STUDY ON BOTDR-BASED DISTRIBUTED MONITORING FOR SLOPE ENGINEERING

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## Abstract

Lattice beams, anchor bolts, slide-resistant piles and retaining walls are widely used in slope engineering to ensure the slope is stable, so the monitoring of slope engineering is a necessary task for geotechnical engineers. A newly developed distributed fiber optic sensing technology ------ Brillouin Optical Time-Domain Reflectometer (BOTDR) has some unique functions such as distributed, long distance, anti-electromagnetic interference, being waterproof, corrosion resistant, and very durable, which is very suitable and useful to the monitoring and early-warning of geotechnical engineering such as slope engineering. In this paper, the measurement principle and merits of BOTDR are introduced, and a BOTDR-based distributed monitoring system for slope engineering is presented, the relative topic are discussed in details, including the layout and installation of the sensing fiber, its protection and temperature compensation, and the calculating method of stress and deflection of the anchor bolt and retaining pile. Finally a case is taken to illustrate the feasibility of this technology.

## INTRODUCTION

Natural or man-made slopes, as a geologic condition, are often encountered in practical engineering. To ensure that the slope is stable and to prevent landslides, the corresponding slope engineering is taken. The monitoring of slope engineering is a very important work in geotechnical engineering for the reduction and prevention of landslide disasters.

At present, the monitoring techniques and methods of slope engineering are changing from conventional point-mode monitoring to distributed, automated, high precision and long-distance monitoring [1, 2]. The conventional sensing technologies, such as vibrating wire sensors and strain gauges, have some disadvantages such as poor anti-interference, poor durability and poor stability etc., which have not met the monitoring requirements of modern geotechnical engineering. A newly developed distributed fiber optic sensing technology-----Brillouin Optical Time-Domain Reflectometer (BOTDR) has some unique functions such as distributed, long distance, anti-electromagnetic interference, being waterproof, corrosion resistant, and very durable, which is very suitable and useful to the monitoring and early-warning of geotechnical engineering such as slope engineering. In addition, the BOTDR-based monitoring technology usually doesn't need special sensors and only needs common communication-use optical fiber both as a signal transmission medium and the sensing body as well. The optical fibers small size and light weight make it easy to install in or on the monitored objects and has well matching with the strain and temperature changes of monitored objects.

BOTDR is a fiber optic strain sensing technique based on spontaneous Brillouin backscattering light. It has been recognized as a powerful distributed monitoring technique with its distributed and long distance measurement, and can measure the strain and temperature distribution along a sensing fiber. In recent years, BOTDR has begun to be applied in the deformation monitoring and health diagnosis of civil and hydraulic engineering, and a series of achievements have been obtained [3~8]. However, little information about the application of BOTDR in slope engineering monitoring has been reported [9~12].

In this paper, the BOTDR-based distributed monitoring system for slope engineering is designed. The layout, installation, protection and temperature compensation of the sensing fiber mounted on frame beam, anchor bolt, slide-resistant pile and retaining wall are introduced. The feasibility of this monitoring technique for slope engineering is investigated through a case study.

## PRINCIPLE OF BOTDR

Brillouin scattered light is caused by non-linear interaction between the incident light and phonons that are thermally excited within the light propagation medium. This scattered light is shifted in frequency by a Brillouin shift and propagates in the opposite direction relative to the incident light. It has been found that there is a linear relationship between the strain or temperature and the frequency shift within the sensing optic fiber. The core technique of BOTDR is Brillouin spectroscopy and Optical Time Domain Reflectometry (ODTR) that enables BOTDR to measure the frequency shift generated in optical fiber when the strain occurs or temperature changes in the longitudinal direction of optical fiber[13]. The linear relationship between Brillouin frequency shift and axial strain or temperature can be expressed as

$$\varepsilon=C_S(v_B-v_{B0})+\varepsilon_0 \qquad (1)$$

$$T=C_T(v_B-v_{B0})+T_0 \qquad (2)$$

where $\varepsilon$ is the strain of optical fiber, $T$ is temperature, $C_S$ is the strain coefficient of Brillouin frequency shift, $C_T$ is the temperature coefficient of Brillouin frequency shift, $v_B$ is Brillouin frequency shift of optical fiber, $v_{B0}$, $\varepsilon_0$ and $T_0$ is initial Brillouin frequency shift, strain and temperature of optical fiber, respectively.

BOTDR AQ8603 developed by NTT Company was used in this project. It is capable of continuously and simultaneously measuring the strain value at any points distributed along the optical fiber only from one end of the sensing fiber. The measured strain range is ±1.5% and the measured length reaches is 80 km. The measurement accuracy is up to ±0.003% and distance resolution is 1 m. With a network of sensing fibers, the BOTDR can measure the strain distribution of slope engineering. These indexes can meet the requirements of small deformation monitoring of slope engineering. However, to apply BOTDR into practical engineering monitoring, there are still some key problems to be solved as follows: (1) the layout and installation of sensing fiber. Slope engineering is usually composed of several parts of reinforcement structure, so the monitoring work contains various monitoring items and covers large monitoring area. It is necessary therefore to choose an optimal layout and installation method of the sensing fiber; (2) the protection of sensing fiber. The sensing fiber, which is made of common communication optical fiber, is easily damaged and broken during the engineering construction and monitoring, so developing the special sensing fiber and corresponding protection methods is an important research issue; (3) temperature compensation. Since the Brillouin frequency shift measured by BOTDR includes both the strain and temperature information, how to make strain or temperature compensation needs to be solved.

## LAYOUT AND INSTALLATION OF SENSING FIBER ON THE SLOPE ENGINEERING

For the unstable slope or slope with complex geologic conditions, a reinforcing system, which consists of a frame beam, anchor bolt, slide-resistant pile, retaining wall etc., is usually mounted on the slope to raise the slope stability as shown in Fig. 1. In order to evaluate the reinforcing effect of slope engineering and slope stability, the stress and strain state of reinforcing structure should be monitored and analyzed. Using BOTDR to monitor slope engineering, how to lay out and install the sensing fiber on the slope engineering must first be solved.

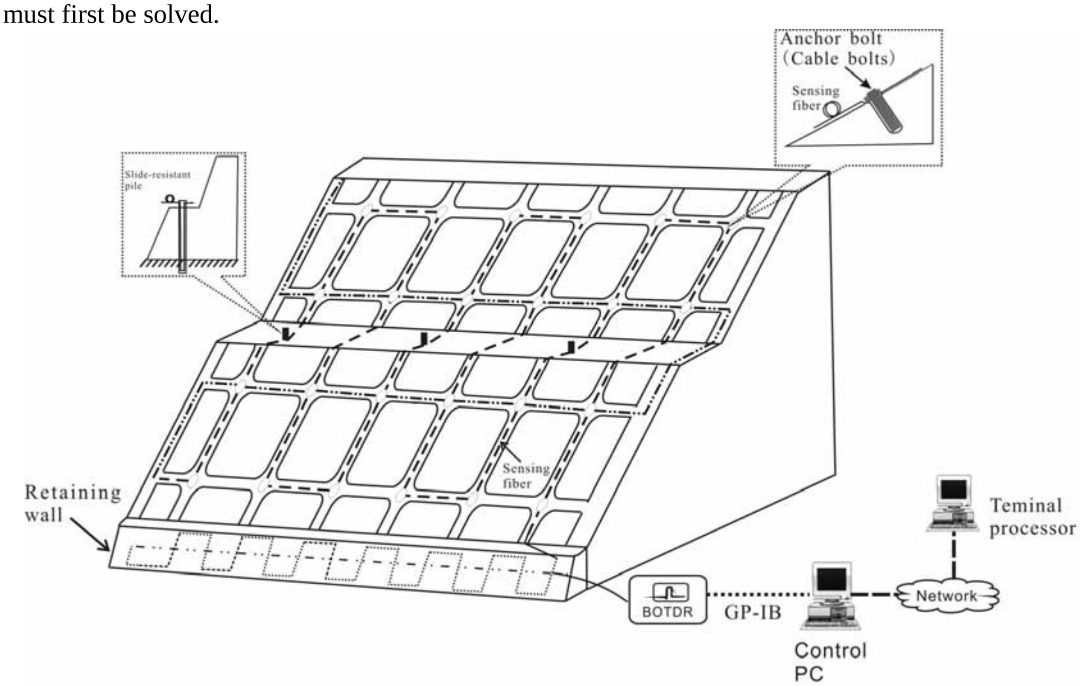


Figure 1. Slope Engineering and BOTDR-based distributed monitoring system

### Layout and Installation of Sensing Fiber on Slope Surface

For the natural and man-made slope without reinforcement, the layout of sensing fiber on a slope surface can be made in a net-shape, (see Fig.2). The installation of sensing fiber must ensure the deformation consistent between the sensing fiber and soil & rock mass. The sensing fiber can be embedded into the soil slope at a certain depth or fixed directly on the surface of rock mass using a steel rod. The temperature compensation of sensing fiber can be realized by measuring a free sensing fiber encased in the PU pipe. According to the monitoring data of the sensing fiber net, the deformation area of a slope surface can be determined.

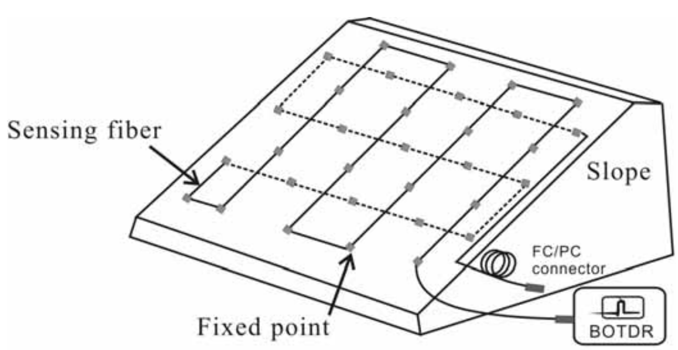


Figure 2. The layout and installation of sensing fiber net at slope surface

**Layout and Installation of Sensing Fiber on Lattice Beam**

A reinforced concrete lattice beam and the anchor bolt are often combined to use for strengthening the slope stability. There are two methods to fix sensing fiber on a lattice beam. The first method is to put the sensing fiber inside lattice beam during its making; the second is to paste the sensing fiber in the groove chiseled on the surface of the lattice beam. Thus, a sensing fiber net is formed to monitor the lattice beam deformation, see Fig.3.

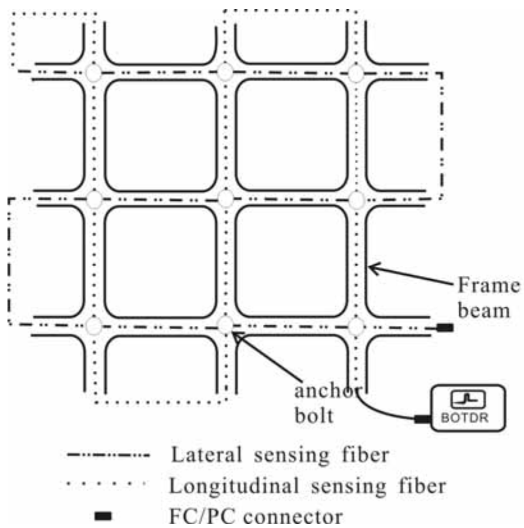


Figure 3. The layout and installation of sensing fiber on lattice beam

The strain increment of sensing fiber net can be measured by BOTDR. When deformations or cracks occur in the lattice beam, the amount and position of abnormal strain on the sensing fiber net can be determined, based on the abnormal strain area on which slope surface can be circled out.

**Layout and Installation of Sensing Fiber on Anchor Bolt and Its Stress Calculating**

The layout and installation of sensing fiber on the anchor bolt is shown in Fig.4. A groove is chiseled on one side of the anchor bolt, and a sensing fiber is put into the groove, and then sealed by the special epoxy resin. The fiber for temperature compensation is loosely laid on the other side of the anchor bolt, which is encased in a PU tube and a ripple-like metal tube to protect it from the damage and to keep it loose. So the configuration of sensing fiber on the anchor bolt is as a “U” shape. The influence of temperature on fiber strain can be eliminated through Eq. (2).

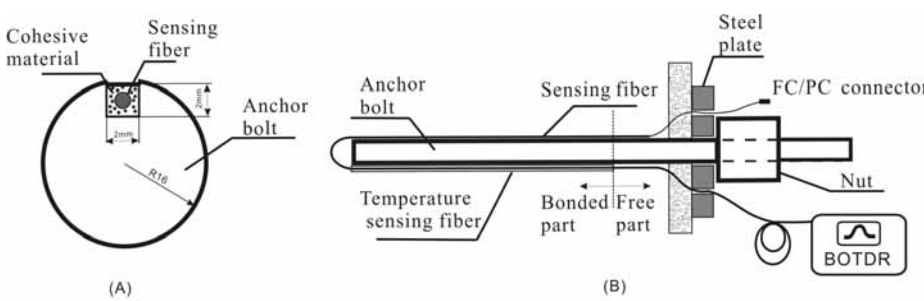


Figure 4. The layout and installation of sensing fiber on the anchor bolt

The sensing fiber of each anchor bolt can be connected in a series to form a single sensing fiber, thus the strain distribution of all anchor bolts inside the slope can be simultaneously measured by BOTDR from one end of the sensing fiber. According to the following Eq. (3), the axial stress of anchor bolt and its distribution curve can be obtained. The average shear strength along the anchor bolt can be calculated based on the strain values of two adjacent points using Eq. (4), and the distribution curve of shear stress can also be found.

$$\sigma_i = E\varepsilon_i \tag{3}$$

$$\tau_j = \frac{(\varepsilon_{i+1} - \varepsilon_i)EA}{\pi D \Delta l} \tag{4}$$

where $\sigma_i$ is the stress of point i on the anchor bolt, $E$ is elastic modulus of the anchor bolt, $\varepsilon_i$ is the strain of point i on the anchor bolt, $\tau_j$ is the average shear stress between point i and i+1 on the anchor bolt, $A$ is the area of the section of the anchor bolt, $D$ is diameter of the anchor bolt, $\Delta l$ is the distance between the two adjacent points on the anchor bolt.

**Layout and Installation of Sensing Fiber in a Slide-Resistant Pile and Its Deflection Calculation**

The slide-resistant pile is usually made in situ, so the reinforcing steel bars inside the pile can be as a carrier for setting the sensing fiber, as shown in Figure 5.

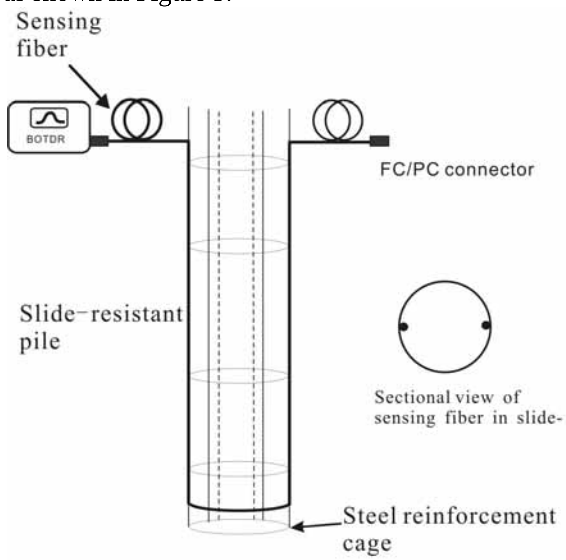


Figure 5. The layout and installation of sensing fiber in a slide-resistant pile

The sensing fiber is planted in the pile in a U-shape and a free sensing fiber is placed in the PVC pipe as a temperature compensation fiber.

Bending would occur in a slide-resistant pile because of the rock and soil pressure. The bending makes the sensing fibers on both sides of the pile body tensile and compressive respectively, and the accidental strain can be measured using BOTDR. The bending of the slide-resistant pile can be simplified as a cantilever beam. The deflection can be calculated as follows:

$$\upsilon(x) = \iint\left(-\frac{\varepsilon(x)}{y}\right)dxdx \tag{5}$$

where $v(x)$ is the deflection; $y$ is the distance between the sensing fiber and the middle plane of the pile; $\varepsilon(x)$ is the stain of the sensing fiber. The strain data measured by BOTDR is discrete by a certain interval along the axial direction of the fiber, so after discretizing Eq. (5), we can get:

$$\upsilon(x_n) = -\frac{1}{y}\sum_{i=1}^{n}\sum_{i=1}^{n}\varepsilon(x_i)\Delta x \Delta x \tag{6}$$

where $\Delta x$ is the spatial sampling interval of BOTDR; $x_i$ is the coordinates of the strain $\varepsilon(x_i)$, equal to $i\Delta x$.

### Layout and Installation of Sensing Fiber on Retaining Wall

The installation of sensing fiber on a retaining wall can be done in two ways, i.e. embedding and surface pasting. As shown in Fig. 6, a sensing fiber net is made for monitoring a retaining wall. When the deformations and cracks occur, the location of abnormal parts can be determined in light of the monitoring data of sensing fiber net. Based on long-term monitoring data, the stability of the retaining wall can be evaluated.

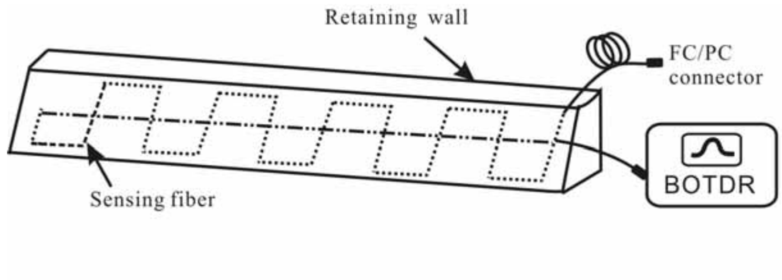


Figure 6. Layout and installation of sensing fiber on retaining wall

### BOTDR-Based Monitoring System of Slope Engineering

The slope engineering mounted by the sensing fiber can be called intelligent engineering. The sensing fiber is like the nerve in our body to perceive the strain change of a lattice beam, anchor bolt, slide-resistant pile and retaining wall etc. The sensing fibers on the various parts of slope engineering can be connected in a series or get together to link into an optical cable that is connected to the BOTDR demodulator. Using GP-IB cable, the monitoring data in BOTDR can be transferred to the control PC for data processing, and also be sent to the remote terminal processor via wireless internet. The scheme of monitoring system is shown in Fig. 1.

## A CASE STUDY

To illustrate the feasibility of BOTDR-based monitoring technology for slope engineering, a slope on the Ning-Huai expressway in Jiangsu province, China, is taken as a case. This site is a weak expansive soil slope 8m high with a 1:2 slope ratio.  Some parts of the slope body belong to artificial fillings. To fix the sensing fiber on the slope surface, as introduced in above section 3.1, drill rods were used to fix the sensing fibers with intervals of 5m, and plunging depth of the rod is 0.5m. The fiber was put in at a depth of 10cm under the slope surface, thus a distributed sensing fiber net was installed on the slope surface as shown in Fig. 7. To make temperature compensation, a free fiber was put in the PU pipe, and was installed between the 3rd and 4th line along the slope.

Figures 8 and 9 show the monitoring results of BOTDR for the slope after one week of rain. It can be seen from Fig. 8 that there is an about 10m of abnormal segment on the strain curve of a-b-c section of line A, and about 15m of the abnormal strain segment i-j-k-l as shown in Fig. 9. So the deformation area of the slope surface can be estimated as shown the shadow area in Fig. 7.

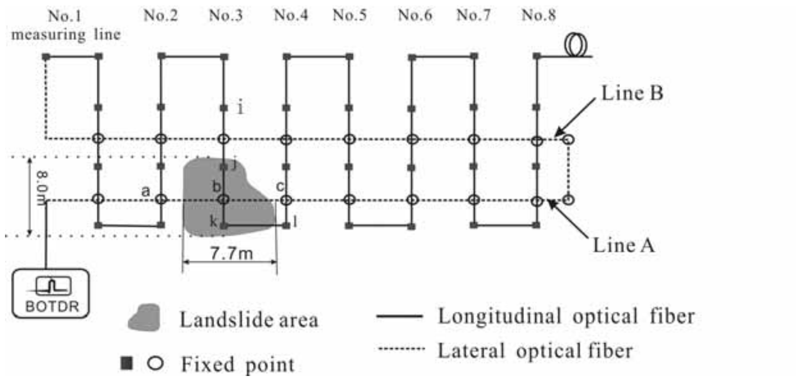


Figure 7. The layout and installation of sensing fiber on the slope surface

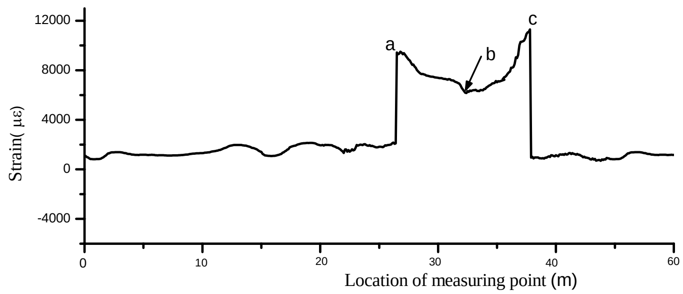


Figure 8. The strain monitoring result of Line A

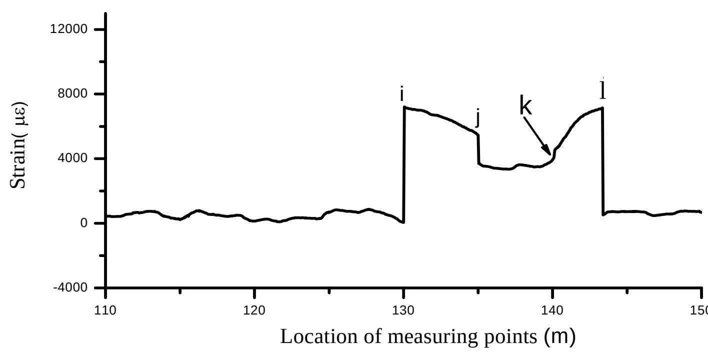


Figure 9. The strain monitoring result of the line No.3

On the in-situ investigation, the sliding of this area was confirmed, (see Fig. 10). The sliding area along line A is 7.6m in length, and 8m along the 3rd line, which scale are less than that of the monitoring result of BOTDR. This is caused because the length of the tensile sensing fiber between two fixed nodes of sensing fiber is more than the actual soil sliding length. On line A, the movement of node b causes the tension of section a-b and b-c of the sensing fiber, as a result, the measured deforming length of the sensing fiber is more than the actual one; Along the 3rd line, the movement of node j causes the tension of section i-j, and the movement of node k causes the tension of section j-k and k-l at the same time.

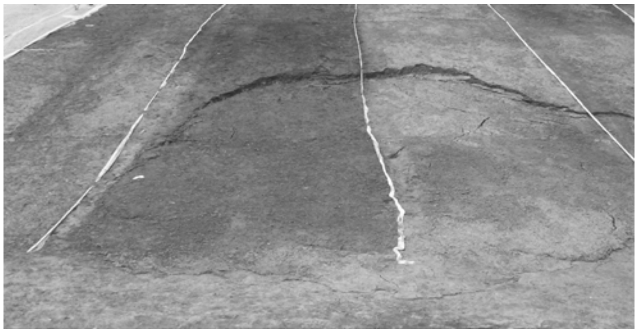

Figure 10. Slope deformation

The above monitoring results indicate that the BOTDR-based distributed monitoring technology can be applied to monitor slope deformation and sliding, and determine the spatial deforming area. The monitoring results can meet the early-warning requirement of landslides.

## CONCLUSIONS

In this paper, the layout, installation, protection and temperature compensation of sensing fiber in slope engineering are introduced; the calculating method of stress and deflection of the anchor bolt and retaining pile is presented; the BOTDR-based distributed monitoring system for slope engineering is setup and a case is taken to illustrate the feasibility of this technology. The research indicates that the BOTDR-based distributed monitoring system for slope engineering has some unique advantages through distribution, time-saved, effort-saved, real-time, and on-line monitoring. It can be anticipated that the distributed monitoring technology and its R & D for slope engineering will be an important development and there will be very wide application prospects.

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