The BOTDR-based distributed monitoring system for slope engineering

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Abstract: Conventional monitoring instruments such as displacement meters, pore water pressure manometers and strain gauges are commonly used in slope stability monitoring. These monitoring instruments mostly belong to the single or multi-point mode, so the monitoring results are often affected by the measuring point arrangement. With the development of fibre optic sensing technology, it is possible to make continuous and distributed monitoring for civil structures and slope engineering using fibre optic sensing technologies, which can overcome some deficiencies of traditional monitoring technologies. Thus, the distributed fibre optic sensing technologies potentially have a wide application in engineering monitoring. The BOTDR-Brillouin Optical Time-Domain Reflectometer is a recently developed distributed fibre optic strain monitoring technology, which has the advantages of long distance, distributed, interference-free and endurance. It has been applied in the health monitoring of civil engineering and geotechnical engineering. Based on the characteristics of slope engineering, the feasibility of BOTDR's application in slope engineering monitoring is analyzed and a set of BOTDR-based monitoring methods for slope engineering is put forward in this paper. A case study is used to illustrate the implementation procedure and validity of using it. A framework for the BOTDR-based monitoring system for slope engineering is established. Finally, further research and application topics are proposed.

Résumé: Des instruments de surveillance conventionnels tels que des mètres de déplacement, des manomètres de pression d'eau interstitielle et des jauges de contrainte sont généralement utilisés dans la surveillance de stabilité de pente. Ces instruments de surveillance appartiennent la plupart du temps au mode simple ou multipoint, ainsi les résultats de surveillance sont souvent affectés par l'arrangement de poste de mesure. Avec le développement de la technologie de sensation à fibres optiques, il est possible de faire la surveillance continue et distribuée pour les structures et la technologie civiles de pente en utilisant les technologies de sensation à fibres optiques, qui peuvent surmonter quelques insuffisances des technologies de surveillance traditionnelles. Ainsi, les technologies de sensation à fibres optiques distribuées ont potentiellement une application large dans la surveillance de technologie. Le Réflectomètre Optique de Temps-Domaine de Brillouin (BOTDR) est une contrainte à fibres optiques distribuée récemment développée surveillant la technologie, qui a les avantages de de fond, distribué, interférence-libre et la résistance. Il a été appliqué dans la surveillance de santé du génie civil et de la technologie géotechnique. Basé sur les caractéristiques de la technologie de pente, la praticabilité de l'application de BOTDR dans la surveillance de technologie de pente est analysée et un ensemble de méthodes de surveillance BOTDR-basées pour la technologie de pente est proposé en cet article. Une étude de cas est employée pour illustrer le procédé d'exécution et la validité de l'employer. Un cadre pour le système de surveillance BOTDR-basé pour la technologie de pente est établi. En conclusion, on propose d'autres recherche et matières d'application.

Keywords: strain, monitoring, slope stability, anchors

INTRODUCTION

The characters of geo-linear infrastructure and its requirements for the health monitoring are as follows: (1) a large scale, such as tens or hundreds of kilometers of tunnels and embankment; (2) a big diversity of engineering environment. Some of geo-linear infrastructure such as oil pipes sometimes transit the various geographic areas and time periods and its engineering environment is quite complex; (3) high requirements of real-time and long-distance monitoring for some infrastructures such as special soil foundation and slope engineerings, bridge foundation and embankment monitoring during the raining season and flood; (4) high accuracy of monitoring. Some important engineerings such as large-span tunnel, underground facilities and bridge foundation require the order of micron or millimeter measure accuracy. Hence the conventional measure and monitoring methods and techniques are more and more not to meet the monitoring demands for geo-linear infrastructure health monitoring.

Recently, the Brilliouin Optical Time Domain Reflectometer (BOTDR) has been recognized as a powerful distributed fibre optic sensor with its real-time monitoring, long measurable distance, high measurement accuracy and high durability, and has been applied in various infrastructure engineering's deformation monitoring and health diagnosis such as tunnel, embankment, bridges and subway (Haruyoshi, 1997; Liu,1999; Qiang,1999; Wu,2000;Yang, 2000; Bao, 2001; Ohno,2001; Shi, 2003a, 2003b, 2004) .

THE PRINCIPLE OF BOTDR

The core technique of BOTDR is Brillouin spectroscopy and Optical Time Domain Reflectometry (ODTR) that enables BOTDR to measure strain generated in optical fibres as distributed in the longitudinal direction. When the strain occurs in the longitudinal direction of optical fibre, the backscattered light of Brillouin undergoes a frequency shift that is in proportional to the strain. Brillouin frequency shift is function of strain ε and can be expressed by equation (1):

$$\nu_B(\varepsilon) = \nu_B(0) + \frac{d\nu_B(\varepsilon)}{d\varepsilon} \cdot \varepsilon \tag{1}$$

where $\nu_B(\varepsilon)$ is Brillouin frequency shift with strain; $\nu_B(0)$ is Brillouin frequency shift without strain; $d\nu_B(\varepsilon)/d\varepsilon$ is the proportional coefficient of strain that is about 0.5 GHz (/ % strain) at the wavelength λ =1.55 μm; and ε.is the strain.

The pulse light is launched into one end of an optical fibre, and the Brillouin backscattered light occurs and is detected at the same end. The distance Z from the launched end of the optical fibre is given by the equation (2):

$$Z = \frac{c \cdot T}{2n} \tag{2}$$

where c is velocity of light in a vacuum; n is the index of refraction of an optical fibre; and T is the time interval between launching pulse light and receiving the scattered light.

The detection principle of BOTDR is briefly outlined as follows: a continuous light emitted from the DFB-LD laser light source can be separated into the probe light to be output to the optical fibre to be measured and the reference light for heterodyne detection. The probe light can be modulated into the pulse light by an intensity modulator. The Brillouin backscattered light takes place as the pulse light launched into the optical fibre interact with the acoustic phonons, and the frequency shift of Brillouin backscattered light occurs compared with the frequency of the launched pulse light. The frequency shift amount is in proportion to the longitudinal strain of the optical fibre (Haruyoshi *et al.* 1997). Figure 1 shows the measurement diagram of BOTDR.

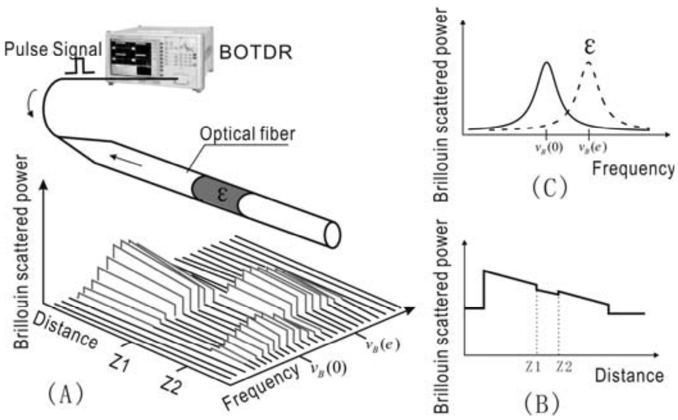

Figure 1. The measurement diagram of BOTDR

Compared with the conventional strain monitoring techniques, the merits of BOTDR can be summed up as the follows:

(i) Distributed. BOTDR can continuously and simultaneously measure the strain of the structure at any points distributed along the optical fibre only from one end of an optical fibre. With a network of optical fibres, the BOTDR can perform full scale monitoring for the structure, which is very difficult or impossible for the conventional point-mode monitoring techniques to do it.

(ii) Long distance. Large infrastructures such as tunnel, dike, oil pipe, subway and large bridge often span the tens or hundreds of kilometres, which is too long for the conventional point-mode monitoring techniques to monitor and measure the deformation distributed in various parts of the structure, however, BOTDR can do that due to its long monitoring distance of over 80 km. On the other hand, the optical fibre in BOTDR serves as both the sensor and the signal transmission medium, so BOTDR is able to monitor the structure from the remote monitoring centre and doesn't need somebody in the site to do it.

(iii) Resistibility. Optical fibre is made of a non-metal, quartz-glass, so it has the resistance of rusting and environmental erosion, and can be used in most of severe conditions such as humid or arid, high or low temperature. In addition, it can protect itself from the electric and electromagnetic interference and avoid the signal error in transmitting process.

(iv) Compatibility. The optical fibre is thin, flexible and lightweight, so it is easy to install it in or on the structure without degrading the structure's strength.

(v) Accuracy. BOTDR can detect as little as 30 μm displacement along the optical fibre, and its distance resolution can reach less than 1m, which are able to meet the needs of large infrastructure engineering health diagnosis.

APPLICATIONS IN SLOPE MONITORING

One of the most common and important geological problems is the slope stability encountered during and after building road in mountainous areas. Regularly the stability monitoring and health diagnosis are imperative to the natural slope and slope engineering with potential sliding. Commonly the slope monitoring includes two aspects: one is the deformation monitoring of the rock and soil mass on the slope surface and the deep, and of the retaining wall, anchor cable and frame beam; the other one is the stress and pressure monitoring of the of the rock and soil mass and retaining wall. Conventional monitoring methods include the inclinometer, crack detector, reinforcement stress detector and displacement meter. Obviously these monitoring methods are of point-mode and cannot meet the monitoring requirement for the whole slope stability, especially for large-scale slope. In addition the conventional measure instrument are often incompatible with rock-soil mass deformation, and the installing difficulties and bad measure circumstance often make the measure point fail and the measure results unbelievable.

BOTDR-based distributed optical fibre sensing monitoring system for the slope has been developed by our research group in 2004. The monitoring system consists of a network of sensing optic fibre, BOTDR, a control PC with data processing software. The system advantages are that it is able to continuously measure the strain all of the parts with sensing optical fibre of the slope engineering structure such as the anchor cable, frame beam and the deep rock-soil mass from only one end of an sensing optical fibre. Through optical cable the sensing optic fibre can be connected to the monitoring station, then BOTDR is able to monitor the slope deformation indoors to avoid on-site monitoring in bad weather. If the control centre is far from the monitoring station, wireless transmitting technology can be used to transmit the data to the control PC located in the control centre and thus realize the long-distance monitoring (Figure 2).

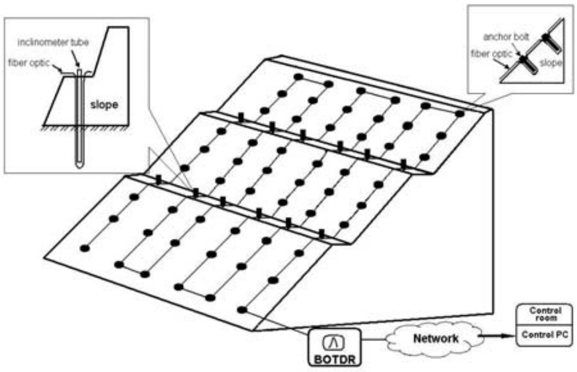

Figure 2. The diagram of BOTDR-based distributed fibre optical sensing monitoring system for the slope

From Figure 2, it can still be seen that the strain of anchor, inclinometer and frame beam can be monitored through a sensing optical fibre, as a result, the whole slope deformation and developing trend can been monitored and the slope stability can be evaluated health diagnosis of slope engineering obtained based on it. Recently the CEMOES of Nanjing University are monitoring two slopes located on a highway using this system, the monitoring work is in progress. Figure 3 shows the installation of the anchor cable with sensing optical fibres into the slope.

Figure 3. Installation of the anchor cable with sensing optical fibres into the slope

Figure 4 illustrates the time history plot of strain distribution along the K3-04 anchor axis. From figure 4 it can be seen that the strain tends to increase from Jan 17 to July 10, 2005 because of the slope creep during raining season, and the maximal strain is 987με, which is found near the top of the anchor. Until now the maximal strain is far below the ultimate bearing capacity of the anchor, so the anchor system operation is under the safe situation. Because the monitoring task is still in the process and much data have not obtained, the ultimate assessing results about the slope stability cannot be reached yet.

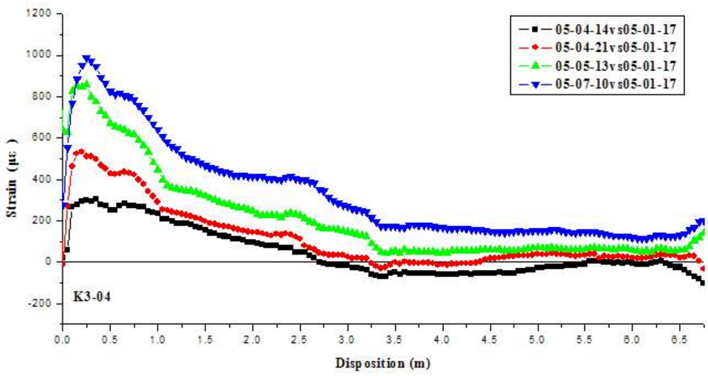

Figure 4. The time history plot of strain distribution along the K3-04 anchor axis

CONCLUSION

On the basis of the above monitoring results and analyses, it is demonstrated the BOTDR with distributed measurement, long-distance and resistibility is quite applicable to the slope engineering monitoring and health diagnosis. However, there are still some techniques such as the optic fibre protection, temperature compensation to be need solved. As the research goes further, we believe that the application techniques of BOTDR will continuously be improved and its application field will be wider and wider.

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