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Review on the application of distributed optical fibre sensing in slope monitoring

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Abstract. The catastrophic event of slope failure which leads to the destruction of surrounding facilities and the loss of public lives has been acknowledge to be one of the most discussed topics in geotechnical engineering. Many conventional and modern techniques have been developed by researchers throughout the years to come out with a technique that is effective in monitoring slope deformation and thus, control the damage that may be caused by slope failure. Recently, the application of optical fibre sensing (OFS) has gained wide attention among researchers in slope monitoring application. It is known that OFS carries many advantages in terms of high resistivity towards electromagnetic interference, wide sensing range, and easy installation. This paper presents the overview of the recent development and application of OFS application in slope monitoring. Two main types of OFS namely Fiber Bragg Grating (FBG) and Distributed Optical Fibre Sensing (DOFS) which consists of Brillouin Optical Time Domain Reflectometry (BOTDR) and Brillouin Optical Time Domain Analaysis (BOTDA) are discussed in detail.

1. Introduction

Landslide is one of the most common natural phenomena which results in the catastrophic destruction of surrounding buildings, facilities and even loss of lives. It can be triggered by several factors such as intense rainfall, earthquake and rapid stream erosion [1]. In fact, [2] has also shown that 14% of economic losses and 0.53% deaths across the globe were caused by landslide related events. With this, efficient landslide monitoring system is needed in order to detect early soil movement to avoid any further major landslide from occurring.

Researchers and engineers over the past years have been applying conventional instrumentations in slope monitoring works such as the inclinometer, strain gauge, tilt meter, and extensiometer. As effective as they may seem, they still possess some limitations which may jeopardize the monitoring result. Take the conventional inclinometer for example, one of the most commercially available devices and commonly used on site, has drawbacks such as high requirement of cable installations, expensive, prone to electromagnetic interference and incapable of real-time monitoring. With the advancement of technology, optical fibre sensors (OFS) has become the centre of attention in recent years as a monitoring device with advantages such as low operational and management cost, high resistance towards electromagnetic interference, accurate data acquisition, and capable of remote transmission and monitoring. In recent years, many applications involving the OFS can be observed in industries such as biomedical engineering [3, 4], aerospace engineering [5, 6], structural engineering [7–9], and robotic engineering [10–12].

With the success of OFS applications in monitoring strain and temperature changes with high accuracy, geotechnical engineers and researchers have also begun to adopt OFS in slope monitoring. The distributive nature of the data collected by using Distributed optical fibre sensing (DOFS) instead

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of discrete data makes it appealing to researchers as no point along the monitoring device goes without any missing data. Therefore, DOFS is able to replace thousands of single point sensors [13]. The basic principles of DOFS are discussed on the first part of this paper which consists of two main technologies; Brillouin optical time domain Reflectometry (BOTDR) and Brillouin optical time domain analysis (BOTDA) followed by the application of DOFS in slope monitoring.

2. Basic principle of Brillouin optical time domain Reflectometry

BOTDR was first invented by Barnoski and Jensen [14] in 1976. Its measurement principle involves a laser being launched into an optical fibre and when the light interacts with the photons in the produced by the propagation medium, backscattered light is produced. The backscattered light will experience a frequency shift by a Brillouin shift if there is a strain or temperature change occur along the fibre. The relationship between Brillouin frequency shift and temperature or strain [14] can be expressed as shown in equation (1)

$$v_B(\varepsilon,T)=v_B(0,T_0)+C_1\varepsilon+C_2(T-T_0) \qquad (1)$$

Where $v_B(\varepsilon,T)$ is Brillouin scattered frequency shift with strain at a certain temperature, T , $v_{\mathbf{B}}(0,T_0)$ is Brillouin scattered frequency shift without strain at initial temperature, T_0. C_1 and C_2 are the strain coefficient and temperature coefficient respectively.

3. Application of BOTDR in slope monitoring

In the recent years, BOTDR has gained popularity among geotechnical researchers as a mean of slope deformation monitoring with the aim to replace conventional instrumentations. As reported by Wang et al. [15], fibre sensors were bonded onto geotextiles and installed into the soil. At some locations, the fiber sensors were also planted directly into the soil without being attached to geotextiles. The test was carried out in a small scaled laboratory model and because of that the spatial resolution of BOTDR is not sufficient resulting in inaccurate strain measurement. In order to improve the accuracy of data acquisition, the test model should be made larger. Apart from that, Shi et al. [16] has also applied the BOTDR technology in slope engineering application where optical fibre cables were attached to anchor cables. These anchor cables were installed on an on-site slope. During rainy season, the slope was reported to creep and the strain resulted from this phenomenon was able to capture by the fibre optic anchor cables. Schenato et al. [16] presented the application of BOTDR technology in slope monitoring using large-scale model. 2 layers of sensing cables were embedded into the soil along with other sensing probes such as the water pressure sensors, volumetric water content and temperature probes as shown in Figure 1. In this test, the author took the initiative in enhancing the grip of the cable with the soil by coating the cable with a plastic sheath corrugated with small indentations in order to prevent the cable from slippage. When slippage occurs, the strain along the fibre cable will be jeopardize resulting in inaccurate strain measurement. The results from the test showed that optical fibre sensor was able to pick up the strain from the slope deformation and can be concluded that it is a reliable tool for slope monitoring.

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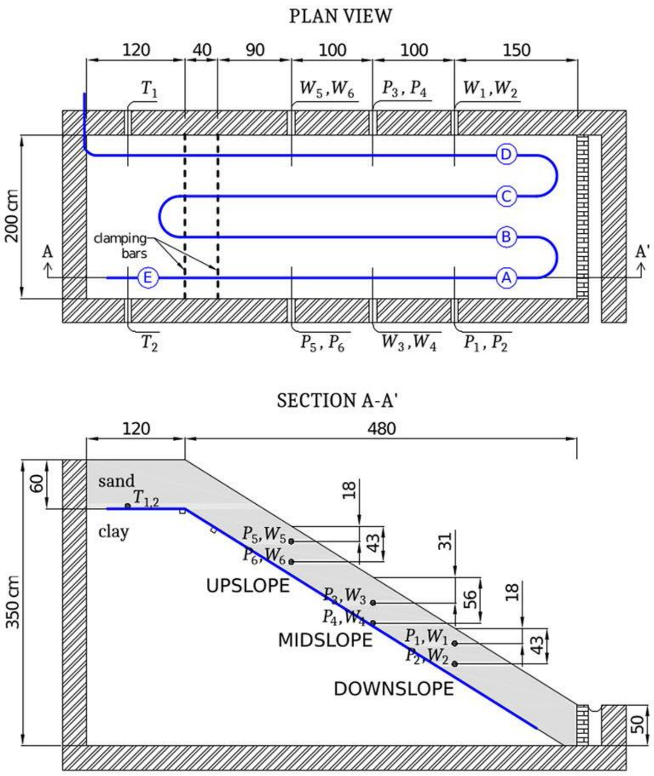

Figure 1. Top and lateral view of the instrumented flume.

4. Basic principle of Brillouin Time Domain Analysis

BOTDA was first invented by Horiguchi et al [17] in 1989. Similar to BOTDR, BOTDA is also a distributed measurement technology which measures the changes in strain and temperature along the optical fibre. Due to these changes, the frequency of the Brillouin backscattered light will change simultaneously which can be expressed in equation (2) [18] :

$$v_B(\varepsilon,T) = v_B(\varepsilon_0,T_0) + \partial v_B(\varepsilon,T)/\partial\varepsilon \times \varepsilon(\varepsilon-\varepsilon_0) + \partial v_B(\varepsilon,T)/\partial T \times (T-T_0) \tag{2}$$

Whre $v_B(\varepsilon_0,T_0)$ are $v_B(\varepsilon,T)$ represents Brillouin scattering light frequency shift before and after the measurement, respectively, ε_0 and ε are the strain before and after the measurement, respectively, $\partial v_B(\varepsilon,T)/\partial\varepsilon$ and $\partial v_B(\varepsilon,T)/\partial T$ are the strain and temperature coefficient with typical values of 0.05MHz/με and 1.2MHz/°C, respectively.

5. Application of BOTDA in slope monitoring

Zhu et al. [19] has conducted a medium-scale laboratory test using BOTDA technology. The model is made up of a slope in steel testing chamber under surcharge loading. Three horizontal layers of optical fibre cable were intalled in the soil as shown in Figure 2. Temperature compensation was also taken care of by looping the optical fibre cable of 1m length at every point.

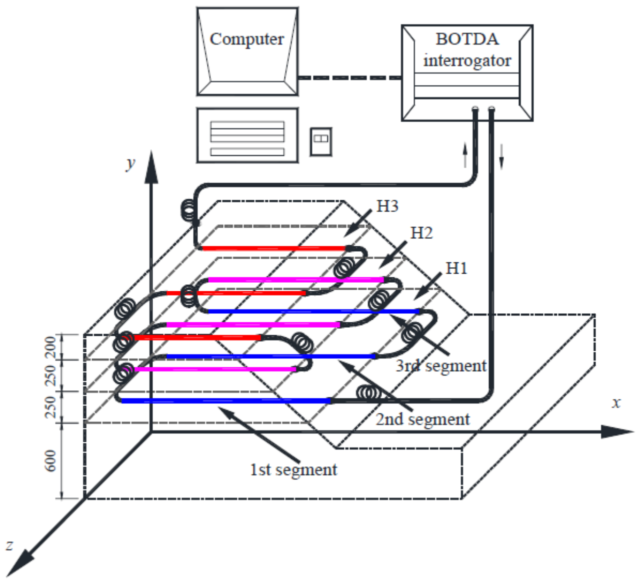

Figure 2. Layout of the BOTDA sensing fibre on the model slope.

This is to ensure that the measurement is only affected by the changes in strain due to the soil deformation and not from the effect of surrounding temperature change. From the result of this test, it is found that there was a direct relationship between the measured strain value and the magnitude of the surcharge loading. The horizontal strain value acquired increased as the surcharge loading were applied at higher value. Another work reported by Yan et al. [20] also applied the BOTDA technology in slope engineering using both horizontal and vertical optical fibre cables configuration in the soil. The horizontal cable configuration was installed in 3 layers as reported in previous research while the vertical cable configuration was installed by first gluing the cables on vertical pipes acting like improvised inclinometer tubes. The results obtained from this test also showed that the strain measurement correlates well with the slope deformation. Although the results in the tests mentioned above showed that DOFS is a feasible method in slope deformation monitoring, the installation of the optical fibre in the soil and the method of gluing the fibre cable on a pipe or other mediums must be standardized. This is to ensure that researchers could eliminate the uncertainties due to the cable installation.

Minardo et al. [21] also reported the application of optical fibre based inclinometer using BOTDA technology by comparing the results with actual inclinometers on site. The cables were installed along the full length of a PVC pipe by using epoxy glue. The configuration of the optical fibre based inclinometer is shown in Figure 3.

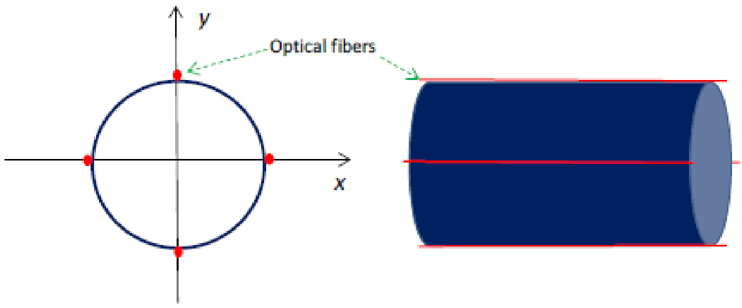

Figure 3. Optical fibre based inclinometer.

Two actual inclinometers were installed on site at a maximum depth of 12m along with the fibre optic inclinometer with a depth of 750cm. Results showed that the displacement of the soil was recorded by the actual inclinometer was to up to the maximum depth of 12m which was unfortunately larger than the depth of the fibre optic inclinometer. However, the fibre optic inclinometer exhibited acceptable accuracy when it was able to detect the maximum pipe displacement at the ground surface.

6. Conclusion

The distributed optical fibre techniques of both BOTDA and BOTDR in the application of slope monitoring have been briefly discussed. From the results obtained by researchers, it can be concluded that DOFS is a feasible and effective geotechnical monitoring tools and has the capability to replace conventional instrumentations. Further improvement in regards to the installation method of the fibre optic cable is still open for discussion in order to come out with the best solution in eliminating uncertainties from the cable installation process.

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