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A new measurement approach for deflection monitoring of large-scale bored piles using distributed fiber sensing technology

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ABSTRACT

A novel distributed fiber optic strain sensing technology, named Brillouin optical time-domain analysis (BOTDA), has been used to study the performance of large-diameter bored piles subjected to a slope excavation in Hong Kong. A new installation method for the distributed fiber optic sensors (FOS) in the bored piles was proposed in this study. Distributed strains along the instrumented bored piles were obtained by BOTDA sensors during multi-stage excavations. Details of sensor design, field installations, sensor protections, and data analysis are presented in this paper. Axial and bending strains along the instrumented pile were obtained by two sets of BOTDA sensors installed on diametrical opposite sides along the pile. The calculation method for deriving the lateral deflections from distributed strains is described. Thus, the calculated lateral deflections from BOTDA sensors were compared with the traditional inclinometers which were installed at the center of the same instrumented bored pile. Measurements obtained from the BOTDA sensors were found to be in good agreement with the inclinometer data. The maximum lateral wall deflection over the excavation depth was between 0.05% and 0.1%. The lessons learned from this field implementation are discussed and suggestions provided for further similar applications. Field application in this study reveals that the BOTDA measurement has great potential to be used for performance monitoring of large diameter piles.

1. Introduction

In the past decade, the demand for safe infrastructures has dramatically increased in Hong Kong, thus a variety of sensors have been developed to meet the requirements for strains and deformations measurement in geotechnical engineering. Over the last few years, fiber optic sensors (FOS) have gained significant interest for health monitoring of civil infrastructures [1–4]. Particularly, the recent advances in distributed fiber sensors based on stimulated Brillouin scattering (SBS) have inspired researchers to explore potential applications in civil engineering [5–8]. The distributed Brillouin analysis was first proposed in 1990s and then developed by many researchers which shown that it has great potential for sensing because the Brillouin scattering is very sensitive to strains and temperatures.

Two commonly used configurations of interrogator for distributed strain sensing technologies based on SBS are Brillouin optical time domain analysis (BOTDA) and Brillouin optical time domain reflectometry (BOTDR) [9–12]. The BOTDR requires access to only one fiber end while the BOTDA needs two fiber ends which are connected in a loop. The BOTDA configuration has two lightwaves (i.e. the pump and the probe signals) which are launched into the fiber so that it makes the BOTDA is a better choice when significant fiber loss during field applications [13].

Over the recent decades, the distributed fiber optic sensing technology has been developed and applied in many civil infrastructures, such as the it was used to measure soil nails response by attaching the sensor on the surface [14]. Mohamad et al. was further extended the application of BOTDR on the monitoring of tunnel deformations [15] and soil slope deformations with fiber-equipped geotextiles [16]. In addition, the BOTDA was developed by many researchers to monitor GFRP soil nails [17], piles [18], soil settlements and landslides [19]. It can be concluded from the literatures that the distributed Brillouin sensing technology was mostly implemented by attaching on the surface or geotextiles of the measurement objects. There are few field studies by using the distributed BOTDA sensors inside the concrete, especially inside of the large-scale bored piles.

In this study, a distributed BOTDA strain sensing system based on standard single mode fibers (SMF) is used to obtain distributed strains and deflections of the instrumented large-diameter bored piles. As compared with the traditional inclinometers and strain gauges, the

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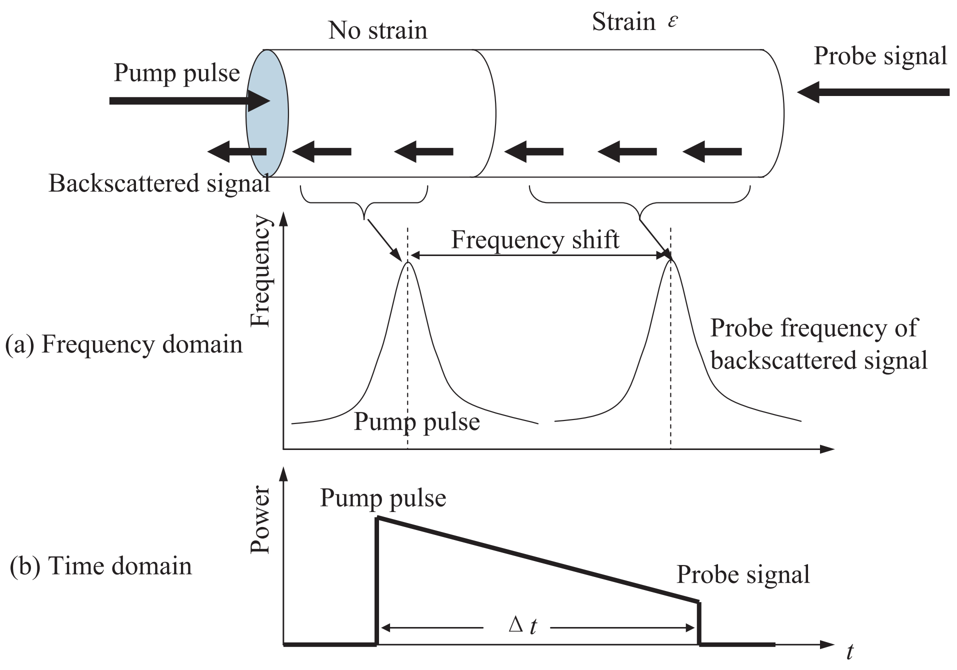

Fig. 1. Measurement principle of the BOTDA sensing system: (a) frequency domain analysis; (b) time domain analysis.

BOTDA sensors have many advantages, such as higher accuracy, tiny size, resistance to electromagnetic interference (EMI) and corrosion, and can measure distributed strains and deflections. However, the inclinometer can only obtain the flexural behavior of a bored pile based on the discrete rotation sensors which cannot determine the distributed strains. Strain gauges can be used to study both axial and flexural behavior, but the accuracy is limited as the stain gauges only provide point measurements which may not be sufficient for studying the soil-pile interactions.

This paper presents a case study of using the new BOTDA distributed strain sensing technology in a field project. The performance of the instrumented bored piles subjected to multi-stage excavations are monitored and analyzed. The aim of the paper is to demonstrate the feasibility of using BOTDA sensing technology to detect the distributed strains and deformations of the bored piles. A new installation approach together with data analysis and interpretations are presented. The measurement results are analyzed and validated with inclinometer readings under various excavation stages. The design of sensors, calibrations, field installations, data analysis, and lessons learned from the implementations are presented and discussed.

2. Principle of BOTDA full-distributed sensing technology

The principle of a BOTDA system is based on the analysis of backscattered signals generated when a pulse of light propagates through the fiber as shown in Fig. 1. A small amount of scattered light is generated due to the interaction between a laser light and fiber material. Strain and temperature change will alter the fiber material and refractive index, and then it will perturb the backscattered light. The Brillouin backscattered light is stimulated by two lights, a continuous optical signal (probe) and optical pulse (pump) which injected to the two ends of the optical fiber. The frequency of Brillouin scattering will be changed with the density of the optical fiber, while the density is dependent on the surrounding temperatures and strains. The Brillouin frequency shift v_B is proportional to the acoustic velocity v_a of scattering medium [9,11].

$$v_B = \frac{2nv_a}{\lambda_0} \tag{1}$$

where n is the refraction index of fiber and λ_0 is the wavelength of the pump. The acoustic velocity v_a is directly related to the material density. As a result, the Brillouin frequency will be shifted due to the variation of temperatures and/or strains. The relationship between the Brillouin frequency and surrounding strains and temperatures can be expressed as follows [9].

$$v_B(\varepsilon) = v_B(0)[1 + C_\varepsilon \cdot \varepsilon] \tag{2a}$$

$$v_B(T) = v_B(T_0)[1 + C_T \cdot (T - T_0)] \tag{2b}$$

where $v(\varepsilon)$ and $v(T)$ represents Brillouin frequency shift at strain ε and temperature T. $v_B(0)$ and $v_B(T_0)$ are the reference frequency. C_T and C_ε are the constant coefficients related to temperature and strain, respectively.

From the above analysis in the frequency domain, the strain values and temperatures can be calculated by the shifted frequency while the positions of the strains and temperatures along the optical fiber should be determined in the time domain. The distance x_i from the pulsed light to the location of generated scattered light can be expressed as

$$x_i = \frac{ct_1}{2n} \tag{3}$$

where c is the velocity of laser in the fiber, n is the refractive index, and Δt is the time interval between the pulse and received back scatted signal.

However, the strain values at any point, x_i along the optical fiber is not an infinitely point. Strain data at any sampling point is an average value over an interval Δx as shown in Fig. 2. This sampling interval Δx is called spatial resolution. According to Horiguchi et al. [9], the spatial resolution (w) is determined by the light velocity and the pulse width of