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# Application of distributed optical fiber sensor for monitoring the mechanical performance of a driven pile

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ABSTRACT

This paper proposes a special application of Brillouin Optical Time Domain Analysis (BOTDA) sensors for monitoring the mechanical performance of a steel H-pile during driving process in a field in Hong Kong. First, basic calibration and the related installation method of optical fiber sensors (OFS) on pile body were introduced. Second, distributed strain profiles along the H-pile during driving process were successfully obtained from optical fiber sensors. Finally, measured strain distributions of the H-pile subjected to two loading/unloading cycles monitored by OFS were used to interpret field performance of the driven pile. Monitoring results indicate that the vertical load applied on the pile head generated significant compressive deformation, which was however mostly released by the corresponding unloading process. The 1st unloading and 2nd unloading processes released around 66% and 72% of the total compressive pile deformation, respectively. The shear stress levels mobilized between H-pile and surrounding soils were limited after each loading/unloading cycle according to the monitoring results. In addition, loading locations on the driven pile can be clearly identified from strain/stress distribution profiles. It is found from the monitoring study that BOTDA based sensors are more useful than some traditional or other point OFS (such as strain gauges or fiber Bragg grating sensors) to evaluate the average strain distribution of large scale structures.

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## 1. Introduction

In terms of sensor distribution, fiber optic sensors may be divided into three categories: (a) point sensors (for example, packaged point fiber Bragg grating sensors; and Fabry–Perot fiber optic sensors) [1–4]; (b) quasi-distributed sensors (for example, multiplexed fiber Bragg grating sensors) [5]; and (c) fully-distributed sensors (for example, Brillouin Optical Time Domain Reflectometry, BOTDR [6]; and Brillouin Optical Time Domain Analysis, BOTDA [7,8]). The BOTDA-based optical fiber sensor is a fully-distributed sensor providing continuous strain and temperature distribution profiles of monitored structures. Therefore, the application of fully distributed optical fiber sensor in practice offers a comprehensive understanding of the mechanical performance of monitored structures.

In recent decades, the fully distributed optical fiber sensor technology has been increasingly used for health monitoring of various geotechnical engineering structures, such as soil nails, piles, slopes, retaining walls, and excavations [4,9,10]. Pile behavior is of great interest to geotechnical engineers and the mechanical performance of a pile reflects not only the strength and stability itself, but also the potential stability issues of the retained geotechnical structures such as retaining walls, foundations, slopes, and excavations [11–13]. A number of typical monitoring projects of

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piles have been conducted based on different optical fiber sensor technologies. Fiber Bragg grating sensor technology is a popular optical fiber sensor for health monitoring of geotechnical structures due to the ease of installation and relatively high sensitivity [14]. Recent years, the FBG sensors were normally multiplexed in series and installed at some specific locations inside piles for monitoring (a) the integrity of foundation piles [3], (b) the load transfer mechanism between soil and piles [2], (c) health condition of composite marine piles [15], and (d) the strain distribution profiles along pile body [16]. According to these studies, proper packaging techniques and protection methods were essentially required for field application of FBG sensors in order to ensure reliable measurement results. For pre-cast piles, the bare FBG sensors were normally placed straightly along a precreated groove along the pile body [17,18]. While for cast-insitu piles, packaged FBG sensors were placed inside boreholes [19] or assembled on steel cages for strain measurement [2].

Fully-distributed OFS have also been widely applied for structural health monitoring of various types of piles [20,21]. For example, investigation of load transfer function of a vertical loaded pile in a layered soil [22], BOTDR based strain and displacement measurement of a secant pile wall [11], displacement monitoring of Geosynthetics using distributed strain and temperature sensing [23], and study of thermal response of pile subjected to heat cycles [6,24]. Since average strain or temperature can be measured using fully-distributed OFS, detailed information with respect to different parameters such as lateral movement, axial load, bending moment, and temperature distribution can be fully obtained and therefore offers in-depth understanding of the pile performance for engineers. Large-scale steel H-pile has been increasingly used in construction industry due to the ease of handling, driving and transportation in practice. Currently the performance monitoring of large-scale steel H-piles based on BOTDA or BOTDR sensors is limited. For driven piles, there is a high probability that OFS could be damaged due to the harsh environment in field. Hence, reasonable design of optical fiber structures, suitable installation method of sensors on piles, careful and suitable protection methods of all optical fiber strain and temperature sensors are essential [20,21].

This paper presents a special application of BOTDA based technique for monitoring the mechanical behavior of a large-scale steel H-pile during the driving process in a real field in Hong Kong. The calibration work of OFS in laboratory, the details of field installation methods of OFS on steel H-pile surface, and the related measured temperature and strain distributions are presented and analyzed. Based on these measured and the related computed quantities, the behavior of the driven steel H-pile is comprehensively evaluated, interpreted and discussed.

## 2. Measurement principle and parameter calculation based on BOTDA technique

### 2.1. Principle of BOTDA technique

BOTDA is an innovative technique proposed for the measurement of light frequency distribution generated by Brillouin scattering effect [25,26], which is stimulated when the frequency difference between continuous wave light and pump pulse light propagating in OFS matches the local Brillouin frequency of fiber core. The measured light frequency change resulted from the Brillouin scattering effect is dependent on the physical properties of OFS in longitudinal direction and therefore can reflect the corresponding strain changes due to external tension or compression. Basic relationship between light frequency $v(\varepsilon)$ and strain $\varepsilon$ is:

$$v(\varepsilon) = v(0)(1 + C_\varepsilon \times \varepsilon) \quad (1)$$

where $v(\varepsilon)$ is Brillouin scattering frequency generated by strain change. $v(0)$ is the reference frequency. $C_\varepsilon$ is constant coefficient corresponding to strain change. The strain coefficient and offset according to the standard calibration test offered by Omnisens Company are 505.5 MHz/% and 10.84 GHz respectively for a standard single mode optical fiber sensor and the related strain resolution is ±0.0001% [27].

### 2.2. Calculation of pile elongation and frictional resistance using BOTDA based sensors

Axial force/stress, frictional resistance distribution, and axial elongation of a pile are critical parameters to geotechnical engineers. BOTDA-based sensor divides the monitored structure into $n$ small elements ($n$ depends on the measurement resolution), average strain of each small element can be obtained from OFS. Deformation of each small element can therefore be written as [26]:

$$\Delta L_i = L_i \varepsilon_i \quad (2)$$

where $\varepsilon_i$ and $L_i$ are average strain and length of each small element, respectively, ($i = 1,2 \ldots n$). The total elongation of the monitored pile $\Delta L$ during driving process can be obtained using the following relationship:

$$\Delta L = \sum_{i=1}^{n} L_i \varepsilon_i \quad (3)$$

For each element, axial stress (denoted by $\sigma_i$) and the related axial force $p_i$ and $p_{i-1}$ at the two ends can be calculated as follows:

$$\sigma_i = E_s \varepsilon_i \quad (4)$$

$$p_i = \sigma_i A = E_s \varepsilon_i A \quad (5)$$

$$p_{i-1} = \sigma_{i-1} A = E_s \varepsilon_{i-1} A \quad (6)$$

where $E_s$ and $A$ are the elastic modulus and cross sectional area of the pile. Frictional force between soil and pile can be obtained by differencing the axial force values at the two ends of the pile element, we have:

$$F_i = p_i - p_{i-1} = E_s A(\varepsilon_i - \varepsilon_{i-1}) \quad (7)$$

where $F_i$ is the occurred frictional force between pile element and the surrounding soil. Therefore, the related frictional shear stress between H-pile and surrounding soil can be calculated by dividing the frictional force with the contact area between pile and soil as below:

$$\tau_i = F_i / KL_i = E_s A(\varepsilon_i - \varepsilon_{i-1}) / KL_i \quad (8)$$

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