Development of Optic Fiber Sensing Technology for Geotechnical Application - From Laboratory Measurement to Geotechnical Monitoring

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Abstract. Optic fiber sensing (OFS) technology has been attracted much attention from geotechnical engineers considering its advantages including small size, light weight, immunity to electromagnetic interference (EMI) and corrosion. It has been applied to provide potential solutions to geotechnical engineering problems. This study first reviews the state-of-the-art applications of OFS in different geotechnical engineering areas, then focuses on several scientific issues in geotechnical engineering from laboratory measurement (determination of effective stress in saturated soils and measurement of surface strain for cylindrical rock sample) to geotechnical monitoring (monitoring the behavior of tree and retaining wall under extreme weathers), finally introduces the advanced methods and transducers based on the optic fiber sensing technology to make contributions to those scientific issues.

Keywords: Optic fiber sensing · Geotechnical engineering · Laboratory experiments · Geotechnical monitoring

1 Brief Review of OFS Application in Geotechnical Engineering

Optical fiber sensing technology is gaining lots of appreciation and acceptance in geotechnical engineering applications. Compared with traditional electrical resistance strain gauges and vibrating wire transducers, OFS takes the lead in many aspects compared with conventional electronic sensors: capable of fully distributed or quasi-distributed measurement rather than discrete measurement; absolute measurement and high sensitivity with the resolution of 1 $\mu\varepsilon$ for strain measurement and 0.1 °C for temperature measurement; and immunity to EMI and corrosion. During the last decade, the innovative development of optical fiber sensors has led to many new applications in the geotechnical engineering field, from laboratory high-accuracy measurement to geotechnical structure monitoring [1].

OFS could be a very useful tool for high-accuracy measurement of strain or temperature [2]. Chen et al. (2020) developed a new measurement device based on fiber Bragg grating (FBG) to determine the radial strains of a soil specimen under both static and cyclic loadings [3]. By laboratory calibration, this transducer is capable of capturing the full range of radial strain during shearing and accurately measuring the radial strain at

H.-H. Zhu et al. (Eds.): BRWSG 2021, LNCE 230, pp. 71–80, 2022.
https://doi.org/10.1007/978-981-16-9963-4_6

the level of 10^{-5} strain. Qin et al. (2021) proposed a novel fiber Bragg grating (FBG) transducer fabricated by 3D-printing technique [4]. This transducer can measure earth and water pressures simultaneously, and the effective stress can be calculated based on the effective stress principle. Hong et al. (2019) developed an FBG pressure cell using the 3D-printing technique, which provides a simple and quick encapsulation method for the fabrication of OFS [5]. FBG sensors have also been implanted at the center of 3D-printed clay soils manufactured by the Addictive Manufacturing (AM) technique to monitor the horizontal strain distributions at different testing conditions [6].

The application of OFS in underground structure monitoring has been studied widely. Wang et al. (2021) utilized FBG sensors to measure radial strains on a buried pipe section and monitor soil-pipe interaction under surcharge loadings and proposed a feasible method to monitor the radial displacement of pipe section under surcharge loading [7]. Song et al. (2021) applied FBG technology to monitor the entire process of tunnel excavation [8]. FBG-based inclinometer for monitoring the deformation in the surrounding soil and FBG sensors attached to the existing piles for monitoring the deformation of piles induced by tunnel excavation was developed and implemented in a tunnel excavation physical modelling study successfully.

Due to the high sensitivity to temperature, the OFS technology has also been innovatively adopted for field monitoring of soil parameters such as water content of natural soils and ice content of frozen soils based on the thermal conductivity difference [9]. Wu et al. (2021) proposed a new method of ice content measurement for frozen soils by measuring the thermal conductivity using the actively heated fiber Bragg grating (AH-FBG) sensors [10]. With the robustness of OFS in extreme environments, those studies developed a reliable tool for long-term monitoring of frozen soils in cold regions to study soil response to climate change, which is very important for many Belt and Road countries.

Slope monitoring is of great necessity for early warning of landslide hazards [11, 12]. As a new sensing technology, OFS plays an important role in slope displacement monitoring. Pei et al. (2020) proposed a new FBG-based inclinometer [13]. Measurement of inclined angle can be achieved by the measurement of magnetostrictive strain under different magnetic fields, which overcomes the limitation of the brittle FBG sensors, which may be broken under large strains or excessive bending. Li et al. (2021) used FBG sensors to measure the strain distribution within a slope model under erosion in a flume test, which shows that the OFS technique can provide precise and stable performance in monitoring slope deformation and the great potential of establishing an effective early warning system for landslides and debris flows [14]. Xu et al. (2021) developed a new risk assessment and monitoring method based on the measurement of large deformation inside construction solid waste landfills using a newly proposed fiber-optic based transducer, which can measure large deformation of up to 1200 mm with high accuracy [15].

2 Development of OFS for Geotechnical Application: Laboratory Measurement

2.1 FBG-Based Effective Stress Cell

Since Terzaghi first revealed the principle of effective stress in 1923, effective stress has been widely accepted as an important and fundamental variable in saturated soils for geotechnical engineering research [16]. However, direct measurement and accurate determination of effective stress have always been a problem for geotechnical engineers. The normal way relies on the utilization of specific transducers such as pore pressure transducer (PPT) and earth pressure cell (EPC). Effective stress in fully-saturated soil is normally estimated by abstracting the pore-water pressure u of PPT from the total stress σ of EPC, as shown in Eq. 1.

$$\sigma' = \sigma - u \tag{1}$$

This traditional method has the following limitations:

(a) Since the effective stress is determined by the calculation of the measured pore-water pressure and total stress, the accuracy of this method relies on the resolutions of both transducers: PPT and EPC for pore pressure and total stress measurement. The errors of either type of transducer will weaken the reliability of the calculated effective stress.
(b) Normally the PPT and EPC are not installed in the same location, and different locations lead to misalignment measurement of pore-water pressure and total stress. Even for the effective earth pressure sensor invented by Correia et al. (2009) using two diaphragms as sensing elements for independent measurement of the total stress and pore-water pressure separately, the stresses on different diaphragms still will not be exactly the same [17].

Considering the above inherent disadvantages of the traditional method, Yin et al. (2020) developed a novel effective stress cell based on the fiber Bragg grating (FBG) sensing technology for direct measurement of effective stress in saturated soil [18]. The working principle of this transducer is based on a different method from Eq. 1.

The design of this novel transducer is shown in Fig. 1. The effective stress cell consists of (1) a thin plate as a "sensing plate" with an FBG sensor adhered to the center of the back surface and (2) a "perforated disc base" on the back of the cell. For field applications where the temperature may fluctuate, a dummy FBG sensor that is mechanical strain-free can be placed inside the cell to measure temperature change and reach temperature compensation. In practical applications, a filter stone/paper covering the perforated disc was used to prevent the perforated disc from being clogged with soil particles. Instead of measuring the pore water pressure, the pore pressures acting on both front and back surfaces of the sensing plate are balanced and do not induce the deflection of the sensing plate. Thus the measured deflection of the sensing plate is caused by the effective stress only.

Figure 2 plots the measured results of conventional transducers and FBG-based effective stress cells under complex overburden pressures. The good agreement of measure

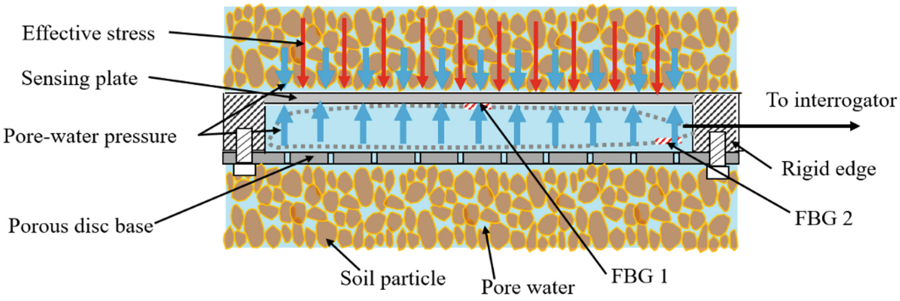

Fig. 1. Illustration of the novel effective stress transducer placed in saturated soil [18]

data by FBG-based effective stress cells and calculated values from the conventional transducers demonstrate that the developed effective stress cell can be utilized in saturated soils subjected to complex loading conditions. Furthermore, the effective stress can be directly obtained with higher accuracy in the measurement and less disturbance on the soil by making use of a single FBG-based effective stress cell, in comparison with embedding two transducers: an earth pressure transducer and a pore-water pressure transducer at different locations for the same purpose.

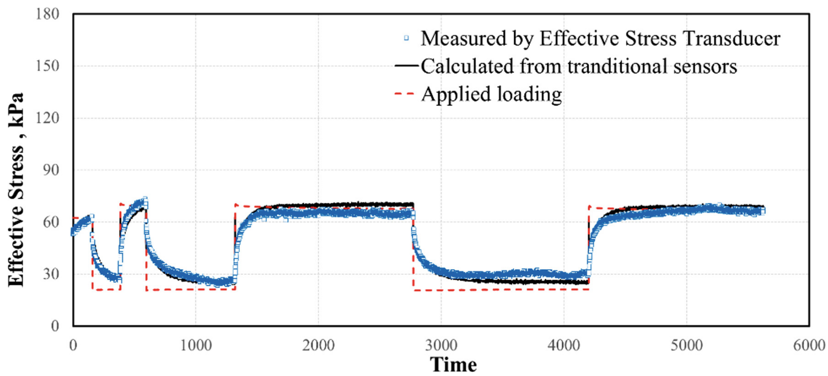

Fig. 2. Comparison of the performance of the novel effective stress transducer with traditional method [19]

2.2 Distributed Fiber Optic Sensor (DFOS) for Surface Strain Monitoring

At present, the uniaxial compression test is one of the basic and widely used laboratory test methods to estimate the mechanical properties and failure mechanisms of rocks through strain measurement [20–22]. Various technologies have been developed for strain measurement in laboratory tests, for example, electrical resistance strain gauges (ESG), linear variable differential transformers (LVDTs), FBG and digital image correlation (DIC) [23–28]. Even though traditional techniques are currently believed to be reliable methods for rock surface strain measurement, they can only provide strain measurement of a single point or at limited locations so that the mechanical properties of rock would be determined by a limited view of the strain field. Digital image correlation (DIC), as a non-intrusive method, has been introduced into strain field measurement because of its capacity for measuring strain distribution within a monitoring window. Currently, the development from two-dimensional (2D) to three-dimensional (3D) DIC solved the measurement errors of 2D DIC caused by the relatively small out-of-plane motions and achieved full-field 3D surface strain measurement [26]. However, there are still some limitations for DIC, for example, dependence on strict external conditions, complicated post-test data processing, and limited strain resolution of 50 $\mu\varepsilon$ [27]. Considering these shortcomings of current techniques for surface strain measurement, Lin et al. (2021) proposed a novel approach to surface strain measurement for cylindrical rock specimens using distributed fiber optic sensing technology [29]. The potential of this method for predicting the possible sequence of crack occurrence and measuring rock crack opening displacement for rock fracturing characteristics research has been further investigated.

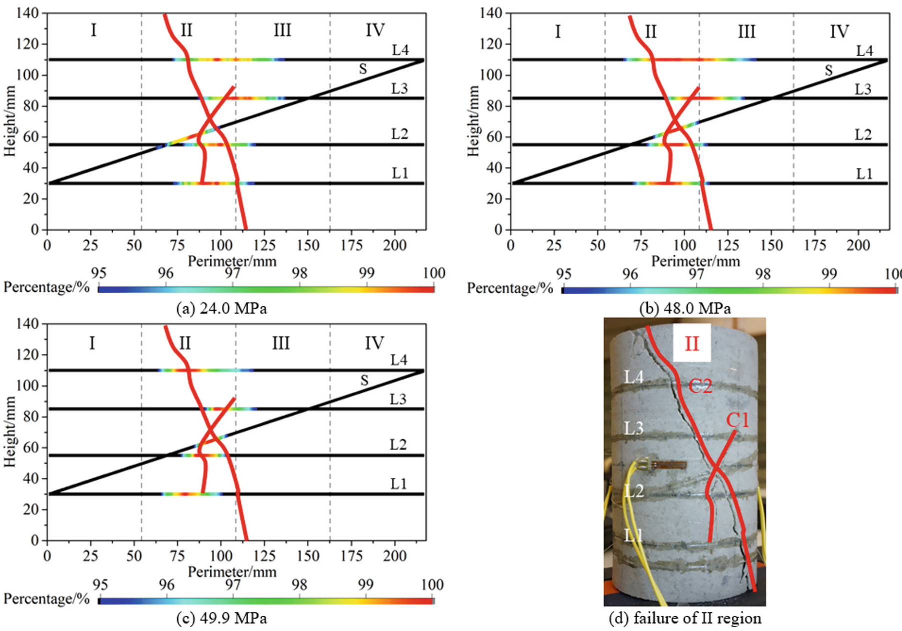

Fig. 3. Strain localization characteristics at different heights in the sandstone under different axial stresses [29]

The OFDR sensing technology adopted in that study can achieve a spatial resolution of 1 mm in a sensing range of 100 m with an outstanding measuring accuracy of $\pm 1\ \mu\varepsilon$, which is fully suitable for strain measurement and micro-crack detection in rocks in laboratory experiments. By gluing a combination of hoop fibers and spiral fibers on the outer surface of a cylindrical specimen, the lateral and axial strains on the specimen surface and the Poisson's ratio of the specimens' material can be measured. Furthermore, the promising performance of this novel approach to surface strain measurement for cylinder rock samples has demonstrated immense potential in local deformation monitoring, especially in those concerning non-uniform deformation. Through a series of UCS tests on rock specimens, this method has been applied to investigate strain localization and possible sequence of crack occurrence, as shown in Fig. 3, and monitor the development of the opening displacements of cracks occurring on the surface of hard rock at a very early stage, as shown in Fig. 4.

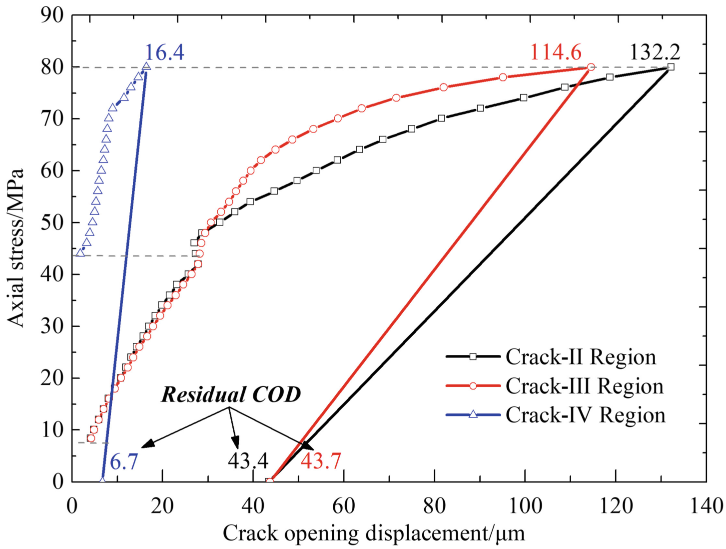

Fig. 4. Development of crack opening displacement (COD) of three selected cracks [29]

3 Development of OFS for Geotechnical Application: Geotechnical Monitoring

Most Belt and Road countries are affected by marine disasters. From the northern part of the South China Sea to the coast of the North Indian Ocean, tropical cyclones (typhoons) are the most common disasters [30]. Optical fiber sensors can directly transform the sensed parameter to the shift of optical wavelength, which is independent of the optical energy, light level, and fiber losses. Apart from the monitoring systems based on conventional electronic sensors, optical fiber sensing techniques, such as fiber Bragg grating (FBG), Brillouin optical-fiber time-domain analysis (BOTDA), and Brillouin optical time-domain reflectometer (BOTDR), have been successfully used for structural health monitoring [31–34].

Since the invention of the first FBG sensor by Hill et al. (1978), FBG sensing technology has shown its advantages in high accuracy, good reliability, immunity to electromagnetic interference, and capacity of multiplexing [35]. Therefore, FBG technology can be a promising technique for monitoring the dynamic behavior of structures. Wu et al. (2021) developed an FBG-based strain gauge specifically for measuring the strain

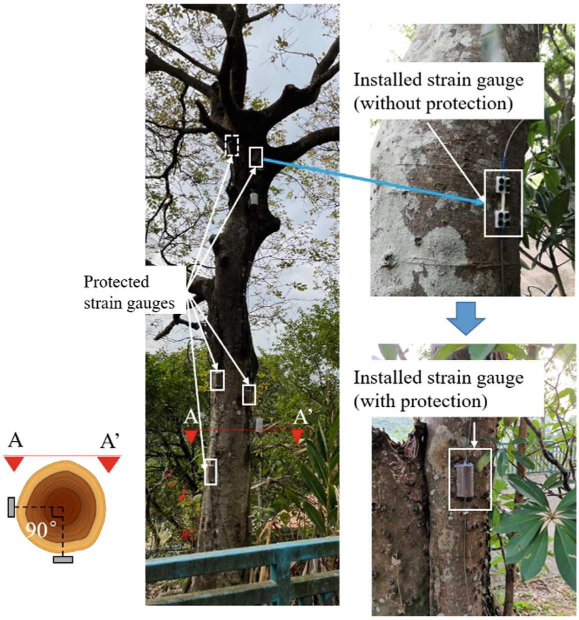

Fig. 5. Arrangement of instrumentation for tree monitoring

distribution of tree trunks under static or dynamic loading and implemented this transducer for the monitoring of tree sway during typhoons [36]. To monitor 2D-strain of the tree trunk under wind loads, a pair of strain gauges were installed perpendicular to each other at the same height of a tree, and the strain at the given height on the tree can be expressed as a combination of two orthogonal components, which are measured by the two strain gauges. A series of FBG sensors can be installed in a row along the tree trunk to measure the strains at different heights, as shown in Fig. 5. From four-month monitoring of dynamic behavior of trees experiencing cyclone disturbance, it is found that this transducer can well capture the dynamic behavior, including the natural frequency of a tree under dynamic wind loads, which is very important for tree stability analysis. If a wind pulse arrives at a frequency near the tree dominant sway frequency, wind force amplifies tree sway as oscillatory motion and may cause tree failure [37]. With the ability to monitor the dynamic response of valuable trees to wind loads, this finding provides a potential application of this transducer in avoiding resonance of trees by proper measures, such as the pruning of tree limbs to prevent possible instability of trees.

Due to the high ecological and cultural values of the stonewall trees and tree-colonized masonry retaining walls in Hong Kong, those structures in service need intelligent health monitoring for evaluating their deformation and safety, further control their possible failures when exposed to severe weathers such as typhoons, heavy rains, increase of groundwater or water pressure. Wu et al. (2021) established a monitoring system for masonry retaining walls, stonewall trees, and large trees. The monitoring system consists of (a) transducers based on FBG sensing technology, (b) data acquisition system, (c) data processing system, (d) remote data transmission module, and (e) solar power system, as shown in Fig. 6 [38]. Optic signals of transducers installed on masonry retaining walls and trees are detected by the data acquisition system and transferred to the data processing system for further analysis. Figures reflecting the dynamic movement of monitored masonry retaining walls and deflection of monitored trees can be plotted and presented on a visualized user interface by analyzing the real-time data of the transducers, which was achieved by MATLAB GUI program. Threshold values for both movements of masonry retaining walls and sway of trees can be pre-set for early warning of possible stability risks. Warning or alarm messages can be distributed to the pre-assigned distribution list once those threshold values are exceeded. Effective and stable coordination between those components enables the establishment of a monitoring system with the following key functions:

(1) Measurement and display of dynamic deflections of trees under wind loads,
(2) Issue of early warnings based on the set thresholds of critical strain and tilt of trees,
(3) Deployment in remote areas with the assistance of a solar power system and 4G data transmission device.

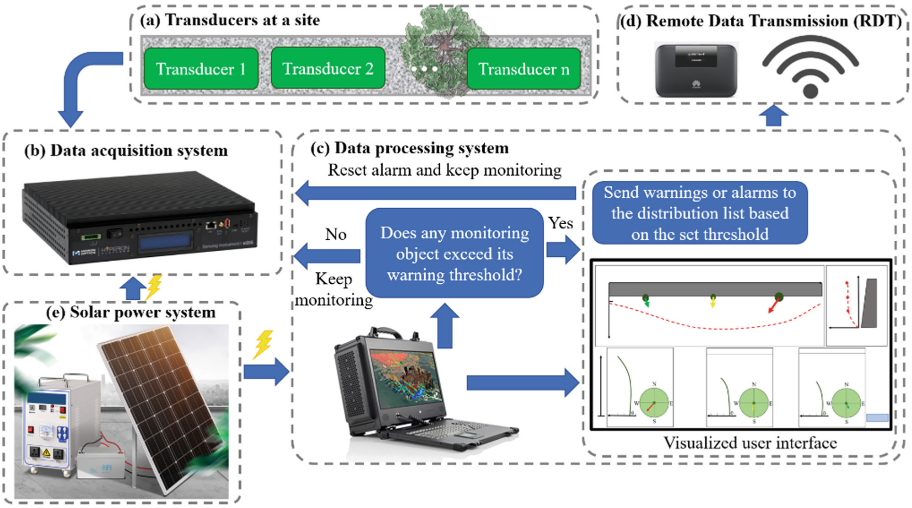

Fig. 6. Illustration of the monitoring system [38]

Four-month successive monitoring has demonstrated the feasibility, accuracy, serviceability, and reliability of the application of optical fiber sensing technology for monitoring dynamic deflections of trees and deformations of masonry retaining walls. Potential of this developed monitoring system includes: (a) study the dynamic behavior of trees under extreme weathers, (b) assess and enhance the resistance of forests under changing climate, (c) investigate efficient measures to manage and prevent possible instability of trees, and (d) provide service life monitoring of important structures and slopes in remote areas.

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