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# Experimental study on pullout performance of sensing optical fibers in compacted sand

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ABSTRACT

The distributed optical fiber sensing systems have played an increasingly important role in monitoring civil infrastructures over the past few years. One of the main challenges of their applications to geotechnical monitoring is to increase the reliability of strain sensing optical fibers in measuring the deformation of surrounding soil masses. In this paper, a pullout test method is proposed to characterize the deformation compatibility between an optical fiber and soil. A series of pullout tests on three types of sand-embedded optical fibers are conducted to investigate the performance of the fiber–sand interface. Based on the test results, an explicit tri-linear pullout force–displacement relationship is proposed to describe the mechanical behavior of the fiber–sand interface. The performance of the three fibers regarding fiber–sand interaction mechanism is evaluated in terms of ratio of effective pullout displacement to diameter, ratio of residual pullout displacement to diameter, peak shear strength and residual shear strength. All four parameters of the three fibers are found to have approximately linear relationships with the applied confining pressure, which reveals that the deformation compatibility of the fiber–sand interface is utterly dependent on the confining pressure. For all the three fibers, the first shear stiffness coefficient is about 8 N/mm and the ratio of residual to peak shear strength is about 0.5. Furthermore, the Mohr–Coulomb failure criterion is used to get the cohesions and friction angles of the three fiber–sand interfaces. Through a comparison of the pullout performance, one out of three types of fibers tested is found to be more preferable for soil deformation measurement in laboratory-scale tests. The conclusions can provide valuable references for predicting the fiber–soil interface behavior and evaluating the reliability of strain monitoring data.

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## 1. Introduction

Geo-materials deform in a very complicated manner. The deformation pattern, trend and scale of geo-materials are greatly influenced by the inherent heterogeneity and anisotropy of ground soil, variability of loading and hydrogeological conditions. As the displacement within ground soil is a critical input parameter for geotechnical engineers, deformation monitoring is considered as essential for geotechnical engineering projects [1]. The existing non-contact measurement technologies, such as Global Positioning System (GPS), Remote Sensing (RS), laser scanning and photogrammetry, can only obtain surface movement data. In addition, most of them have a relatively low accuracy. In the past few decades, various geotechnical

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instruments for monitoring subsurface displacement have been developed. For instance, slope inclinometer, invented in the late 1950s, can monitor the onset and continuation of lateral displacement in a borehole. Another example is borehole extensometer, which is used to measure the axial displacement (distance) between predefined monitoring points in ground soil. Despite the wide applications of these technologies in engineering practices, they can hardly provide remote, real-time and long-term monitoring with high reliability. To perform large-scale or long-distance measurement, a great number of sensors have to be installed, which incurs substantial monitoring cost. Therefore, they cannot meet the urgent needs of modern geotechnical instrumentation, and greatly limit our understanding on deformation mechanism of geo-structures.

Distributed geotechnical monitoring (DGM) is a new concept for geotechnical practitioners. In recent years, the advance of distributed optical fiber sensing (DOFS) technologies enables the simultaneous measurement of strain and temperature profiles over distance up to several kilometers. This has a great deal of potential for geotechnical monitoring. A number of soil structures have been successfully monitored by DGM systems, such as slopes [2–11], foundations [12–15], and tunnels [16–18]. These systems have gained interest from researchers and engineers worldwide by their inherent advantages, including immunity to electromagnetic interference (EMI), high repeatability and durability, tiny size and light weigh, and the ability to multiplex many sensors on one single fiber.

The installation of distributed strain sensing fibers in ground soils is a challenging task as compared with similar tasks in structural monitoring [19–22]. In most cases, the harsh and variable site environment and tight construction schedule do not allow a decent and elaborate installation program. Therefore, it is a common practice to embed the strain sensing fibers directly in soil masses [3–4,7–10,13,18]. This installation method is efficient and straightforward, as stated by Glisic and Yao [23], but uncertainty arises as the deformation compatibility between fibers and soil is unclear. According to the literature, many stress transfer models have been established to describe the interaction between the embedded optical fiber and the surrounding medium, together with a few numerical analyses studies (e.g. [24–33]). However, these interface models cannot take into account the effects of confining pressure, which is a crucial factor for soil inclusions [34–38]. Hence it is impossible to extend these models to interpret the fiber–soil interface. Recently, Zhang et al. [39] proposed a fiber–soil interaction model, which defines five consecutive pullout phases and three working states of a soil-embedded sensing fiber. This model is derived based on limited laboratory test results and the complexity involved in the formulation may bring difficulties to data analysis in engineering practices.

In this paper, laboratory pullout tests were designed and performed to study the interaction mechanism between three types of optical fibers and compacted sand. The test results were interpreted using an explicit pullout force–displacement model. The mechanical properties of optical fiber–sand interface were systematically analyzed and discussed, which led to some conclusions on the performance evaluation of strain sensing optical fibers in geotechnical monitoring.

## 2. Principle of the test design

To study the deformation compatibility and stress transfer rules between sensing optical fibers and the surrounding soil medium, a test method is designed. For a distributed strain sensing optical fiber embedded in soil, which is $D$ in diameter and $2L$ in length, the confining pressure applied on the fiber $\sigma_v$ equals the gravity stress plus additional stress due to uniformly distributed surface loading $p$, i.e.

$$\sigma_v = \gamma H + p \tag{1}$$

where $\gamma$ is the unit weight of soil and $H$ is the embedment depth of the optical fiber.

If the surface loading $p$ increases, the soil will have both settlement and horizontal displacement, which will then induce axial elongation of the optical fiber, as illustrated in Fig. 1(a). It is worth noting that the bending stiffness of the soil-embedded fiber should be neglected [40]. Therefore, under the condition of small differential settlement, the fiber will be tensioned by longitudinal (lateral) soil movement but will not respond to transverse soil movement. According to the load mechanism of the optical fiber (Fig. 1(b)), it can be considered as an axially-loaded cable, which is subjected to fiber–soil interfacial shear stress. Due to symmetry, we will only consider the left half length of the fiber, as shown in Fig. 1(b). If we further assume that a uniformly distributed shear stress at the fiber–soil interface is mobilized by soil deformation, the axial force (or stress) will have a linear distribution along the fiber length (Fig. 1(c)).

In such a case, the strain monitoring data from the sensing optical fiber will be distorted or meaningless if any one of the following conditions happens:

(1) The axial stress acting on the optical fiber reaches its tensile strength. As a result, the fiber material will yield or break.
(2) The induced shear stress at the fiber–soil interface reaches its shear strength. Consequently, relative displacement or even debonding of the fiber–soil interface will occur.
(3) The complicated displacement fields in the soil mass cause the micro-bending and macro-bending of the optical fiber. The optical power loss in the optical path will be enhanced, which will bring more errors to the detection of the fiber-optic readings (e.g. shift of central wavelength for fiber Bragg grating sensors or Brillouin frequency shift for Brillouin Optical Time Domain Analysis sensors).
(4) Large differential settlement occurs in the soil and the transverse movement induces additional strains in the optical fiber. In this case, the large deformation theory should be adopted, which may bring great difficulties to the analysis of strain

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