Quantifying Progressive Failure of Micro-Anchored Fiber Optic Cable–Sand Interface via High-Resolution Distributed Strain Sensing

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Quantifying Progressive Failure of Micro- Anchored Fiber Optic Cable–Sand Interface
via High-Resolution Distributed Strain Sensing

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Abstract:

Distributed fiber optic sensing (DFOS) is gaining increasing interest in geotechnical monitoring. By using soil-embedded fiber optic cables, strain profiles as well as deformation patterns of geotechnical infrastructures can be captured. Probing the fiber optic cable–soil interfacial behavior is vital to the advancement of DFOS-based geotechnical monitoring and our understanding of the soil–inclusion interaction mechanism. To this aim, laboratory pullout tests were performed to investigate the progressive failure of the interface between unanchored/micro-anchored cables and the surrounding sand. High-resolution strain profiles recorded using Brillouin optical time-domain analysis (BOTDA) not only elucidated the influence of anchorage on strain measurements, but also allowed the classical soil–inclusion interaction problem to be studied in detail. Interfacial shear stresses calculated from step-like strain profiles provided clear evidence of the contribution of each micro-anchor to the pullout resistance. The cable–soil contact is a combination of overall bonding and point fixation depending on the level of mobilized interfacial shear stress, and therefore the validity of measured strains is correlated to a three-stage process of interface failure. This study also shows that installing heat-shrink tubes on the fiber optic cable is a rapid, low-cost, effective approach to make an anchored DFOS system for deformation monitoring of earth structures.

Keywords: Micro-anchor; Progressive failure; Interfacial shear stress; Strain distribution; Distributed fiber optic sensing (DFOS)
Introduction

Deformation measurements play an important role from evaluating the performance of massive and complex geotechnical structures to validating and refining relevant analytical and numerical models. Traditional instrumentation using strain gauges, linear variable displacement transducers, inclinometers and extensometers only allow deformation to be recorded at discrete locations or directions, and therefore localized features of the monitored geotechnical infrastructures may not be identified in some cases (Pelecanos et al. 2018).

The distributed fiber optic sensing (DFOS) technology turns common telecommunication fiber optic (FO) cables into sensing elements, which enables continuous strain measurements at kilometre scales and beyond (Shi et al. 2003; Thévenaz 2010; Habel and Krebber 2011; Bao and Chen 2012; Soga and Luo 2018). Recent advances in FO sensing have rendered this technique better suited to geotechnical applications (Schenato 2017; Nöther and von der Mark 2019; Soga et al. 2019). FO cables can be readily integrated into geotechnical structures such as ground anchors, piles, retaining walls, and geosynthetics, because of their geometrical versatility. Recently, field and laboratory attempts have been made to monitor and evaluate the performance of geotechnical structures using quasi-distributed fiber Bragg gratings (FBGs) (e.g., Lee et al. 2004; Zhu et al. 2011; Huang et al. 2012; Zhang et al. 2014b; Borana et al. 2017; Zhu et al. 2017) or Rayleigh and Brillouin scattering-based fully-distributed approaches (e.g., Shi et al. 2003; Klar et al. 2006, 2016; Mohamad et al. 2012; Lienhart 2015; Schenato et al. 2017; Ni et al. 2018; Zhang et al. 2018; Wheeler et al. 2019).

Recent trends aimed at monitoring soil deformation using embedded FO cables have encouraged increased use of micro-anchors (Fig. 1; Iten et al. 2011; Hauswirth et al. 2012, 2014; ASTM F3079-14 2014; Zhu et al. 2014; Damiano et al. 2017). In ground-improvement engineering, anchorages have already been utilized to enhance the pullout resistance of soil reinforcements such as ground anchors (Pérez et al. 2017). For geogrids, the soil in front of transverse ribs is subject to passive earth pressure; this effect, along with the solid geogrid
surface–soil skin friction, results in the mobilized interaction mechanism (Koerner et al. 1989; Bergado et al. 1993; Liu et al. 2009; Moraci et al. 2014). The passive resistance can be further increased by adding anchorages to the transverse elements. One such geogrid named grid-anchor has been introduced by Mosallanezhad et al. (2008) and Alamshahi and Hataf (2009). This was made by attaching short anchors to one side of the geogrid and so greater bearing resistance can be obtained. More recently, Sadat Taghavi and Mosallanezhad (2017) developed an anchored geogrid by adding a set of steel equal angles to the geogrid; the pullout resistance of the new reinforcing system can be increased by up to 65% compared to traditional ones. For DFOS-based geotechnical monitoring, micro-anchors are expected to enhance the interlocking effects between a FO cable and the surrounding soil and therefore extend the measurement range of a DFOS system. Schenato et al. (2017) used the DFOS technology to measure strains exerted on a corrugated FO cable induced by shallow landslide triggering; the evolution of the landslide coincided with the phases identified during the progressive cable–soil failure. Hauswirth et al. (2010) developed a system with three-dimensional micro-anchors attached to a FO cable, and evaluated its performance through pullout and shearing tests. Lately, this system was successfully applied to detect landslide movements in Switzerland (Hauswirth et al. 2012) and ground deformation induced by tunneling in the UK (Hauswirth et al. 2014).

The accuracy of strains measured by a DFOS system with soil-embedded FO cables is subject to the cable–soil interaction mechanism. Probing the cable–soil interfacial properties is thus of great importance for the advancement of both the DFOS technology and our understanding of the interaction mechanism between soil and an inclusion. As such, classical pullout tests have been introduced to study the FO cable–soil interfacial behavior (Iten et al. 2009; Zhang et al. 2014). The test procedure is similar to that of an earth reinforcement such as a soil nail (Wang et al. 2017). The difference lies in that the FO cable is treated as both a soil inclusion and a distributed strain sensor, and therefore no extra strain gauges are needed which might potentially affect the FO cable–soil interfacial properties. In addition, the axial stiffness
of a FO strain cable (equivalent to Young’s modulus multiplied by cross-sectional area) is comparably low, typically in the range between 1–60 kN (Iten et al. 2011; Klar et al. 2016; Schenato et al. 2017). This results in an evident progressive failure behavior of a smooth FO cable in soil under low overburden pressures (Iten et al. 2009; Zhang et al. 2014a). However, until now, the pullout performance of an anchored FO cable embedded in soil has not been investigated in detail. While it is widely accepted that an unanchored soil inclusion has a linear distribution of axial force (accordingly, a uniform distribution of interfacial shear stress) at the critical state (Fig. 2a), these distributions have not been directly measured for an anchored inclusion (Fig. 2b).

In this study, a rapid, low-cost, effective approach was first proposed to make an anchoring system for DFOS-based geotechnical monitoring. Then, laboratory pullout tests were conducted to investigate the micro-anchored FO cable–sand interfacial characteristics. High-resolution strain profiles along the FO cable were captured during progressive interface failure by using a Brillouin optical time-domain analysis (BOTDA) interrogator, which elucidated the influence of anchorage on the measured FO strain data and allowed the soil–inclusion interaction to be studied in detail. Finally, the implications of the experimental results for DFOS-based geotechnical monitoring, as well as the limitations of the present study, were discussed.

**Principle of DFOS using BOTDA**

DFOS is a technology that enables spatially continuous, long-distance, and near-real time measurements along a FO cable. The FO cable itself is not only the transmission medium but also the sensing element. When a light wave generated from a FO interrogator travels through the core of an optical fiber, backscattered lights (Rayleigh, Raman, or Brillouin) are generated at any point along the fiber (Hartog 2017).
For Brillouin scattering (Fig. 3), the frequency shift of the backscattered light is approximately linearly proportional to the axial strain or temperature exerted on the optical fiber (Bao and Chen 2012):

\[
\nu_B = \nu_{B0} + \frac{\partial \nu_B}{\partial \varepsilon} \Delta \varepsilon + \frac{\partial \nu_B}{\partial T} \Delta T
\]

(2)

where \( \nu_{B0} \) and \( \nu_B \) = Brillouin frequency shifts before and after a measurement, respectively; \( \Delta \varepsilon \) = axial strain change; \( \Delta T \) = temperature change; and \( \frac{\partial \nu_B}{\partial \varepsilon} \) and \( \frac{\partial \nu_B}{\partial T} \) = coefficients for strain and temperature changes, respectively. According to eq. (1), if the Brillouin frequency shifts along the entire length of the fiber are detected, a continuous distribution of strain and temperature with respect to distance can be determined. As the spontaneous Brillouin scattering light is very weak, it is recommended to utilize BOTDA to measure strain and temperature along the optical fiber. By deploying the pulse pump and probe at both ends of the fiber, the frequency changes in stimulated Brillouin scattered light can be detected with high spatial resolution and accuracy. Further information about the fundamentals of the BOTDA technology may also be found in Thévenaz (2010), Schenato (2017), and Soga and Luo (2018), which is beyond the scope of this paper.

Materials and Methods

Materials

The soil used in this experimental investigation was a clean, angular river sand. A sieve analysis was carried out and the obtained grain size distribution curve is shown in Fig. 4. From this curve, the values of \( D_{10} \) and \( D_{50} \) were 0.23 mm and 0.35 mm, respectively. The coefficient of uniformity, \( C_u \), was 1.61, and the coefficient of curvature, \( C_c \), was 1.06. The sand was classified as a poorly graded sand (SP) according to the Unified Soil Classification System (ASTM D2487-17 2017). Following ASTM D4253-16 (2016) and ASTM D4254-16 (2016), the maximum and minimum dry density, \( \rho_{d_{\text{max}}} \) and \( \rho_{d_{\text{min}}} \), were determined to be 1.69 g/cm\(^3\) and 1.21 g/cm\(^3\), respectively. By using direct shear tests (ASTM D6528-17 2017), the friction...
angle, $\phi$, of the sand at a relative density, $D_r$, of 23% was measured to be 32.3°. Detailed physical and mechanical properties of the sand are summarized in Table 1.

FO strain sensing cables for monitoring soil deformation have to meet two main requirements, including being robust enough to survive in harsh construction conditions and ensuring efficient strain transfer from soil to the fiber core. A 2 mm-diameter tight-buffed polyurethane-coated FO cable (Nanzee Sensing, Suzhou, China) was used as the strain cable (Fig. 5a), whose performance has been tested in several field monitoring projects as well as physical model tests by the authors’ research group. Detailed properties of this cable are summarized in Table 2. The soft polyurethane coating lowers the Young’s modulus of the cable, which however is still capable of withstanding moderate impacts during installation. Due to its relatively low modulus, it can be easily prestrained and directly integrated into loose material such as soil. Note that this cable was chosen for the current experimental study for that it has shown good performance both in the field and laboratory. However, if the construction activity involves heavy equipment, it is recommended to use cables of higher robustness such as steel strand- or fiber reinforced polymer-buffered cables.

Two types of heat-shrink tube, made of polyethylene (PE) and polymethyl methacrylate (PMMA), were used to make micro-anchors on the FO cable. These two tubes are commonly used to protect a fused optical fiber; they will shrink radially to wrap tightly around the optical fiber by heating with a hot air gun or a built-in heater of an optical fiber fusion splicer. The tubes were shrunk onto the cable coating at a certain interval using a KL-500 fusion splicer (Jilong, Nanjing, China), as shown in Fig. 5b. Two separate FO cables, each having one type of tube, were prepared and tested independently. The average diameter of the micro-anchored cables was calculated according to the anchor distribution, and the average Young’s modulus, $E_a$, of the anchored segments was estimated based on the cross-section geometry. Detailed micro-anchor properties are listed in Table 3.
**FO Interrogator**

The experimental investigation presented in this paper used a NeubreScope NBX-6050A interrogator (Neubre, Kobe, Japan). This instrument provides a minimum readout resolution of 10 mm with a spatial resolution of 50 mm and a noise level of about 7.5 \( \mu \varepsilon \), allowing for distributed measurements along a FO cable of 1 km. The spatial resolution, which is a key factor affecting strain measurements, achieved using the BOTDA technology is higher than that of the Brillouin optical time-domain reflectometry (BOTDR) technology (normally, 500–1000 mm; Shi et al. 2003; Pelecanos et al. 2018). Here, the minimum readout resolution (i.e., 10 mm) and the highest spatial resolution (i.e., 50 mm) of this BOTDA interrogator were adopted to obtain optimal measurements at a laboratory scale.

**Test Setup and Procedure**

A schematic drawing of the test setup is shown in Fig. 6. The test container was 1500 mm long, 200 mm wide, and 200 mm high, made of aluminum alloy walls, 15 mm thick, having a 60 mm-diameter hole in the middle of the front wall. The width and depth of the test container were 100 times the cable diameter and therefore the boundary effect during testing was avoided.

The test bed was prepared using a sand raining technique. When the prepared sand reached the mid-height of the test container, it was gently levelled out and the FO cable centered carefully in the container. The depth of sand above and below the cable was 100 mm. No additional confining pressures were applied on the surface of the sand bed. The density and water content of the sand measured after testing were 1.32 g/cm\(^3\) and 1.92%, respectively. This corresponded to a relative density, \( D_r \), of 23%, indicating that the sand sample was in a loose state (Mitchell and Soga 2005). The embedded cable length was 1200 mm, whereas a 200 mm-long free segment was left between the embedded cable and the front wall of the container to minimize boundary effects. A special clamp having two rubber pieces acting as a cushion was utilized to clamp the free cable segment (Fig. 7); the clamp was then connected to a tensile
tester. The free segment at the other end ran from the top of the test container. Finally, the free
segments at both ends of the cable were connected to the FO interrogator.

Prior to the test, a zero measurement was performed using the FO interrogator to record
the initial strain distribution along the FO cable. During testing, the pullout displacement was
applied using an electric motor with a velocity of 0.1 mm/s and was later calculated according
to the motor speed and time elapsed; the pullout force was recorded using a force gauge with a
resolution of 0.1 N. At each displacement step of 1 mm, the displacement was maintained until
a strain measurement was performed using the FO interrogator.

Preliminary tests were carried out to ensure the suitability of the test setup and procedure.
Afterward, micro-anchors with two different diameters, i.e., \( D_a = 3.6 \) mm and 6.0 mm, were
investigated. A smooth cable without micro-anchors was also tested for comparison.

Results

Characteristics of Pullout Force–Displacement Curves

Curves of pullout force, \( F_0 \), versus pullout displacement, \( u_0 \), are shown in Fig. 8. Notice that
the elongation of the free cable segment was deduced from the measured displacement. A
nonlinearity was observed from the curves before the peak pullout force was reached, due to
the partial failure of the cable–soil interface. This was expected because the axial stiffness of
the cable was comparatively low and therefore progressive failure was evident during testing
(Zhang et al. 2014a).

Moreover, there was only a slight difference between the slopes of the initial sections,
which was confirmed by the secant interfacial shear stiffness calculated at a displacement step
of 2 mm, with the average value being 198.7 kPa/m (Fig. 9). This indicated that the effect of
anchorage on the cable–soil interfacial shear stiffness was not obvious. On the contrary, its
influence on the peak pullout force and peak interfacial shear stress (ISS) was much more
pronounced. For the unanchored cable, the pullout force peaked at a displacement of
approximately 3.82 mm and then reduced with increasing displacements. This illustrated that the unanchored cable–soil interface exhibited a strain-softening behavior during pullout, which agreed well with the results of Zhang et al. (2014a). In contrast, a strain-hardening behavior was observed for the micro-anchored cables, which largely increased the peak ISS (Fig. 9). The peak ISS was increased by 78.48% and 146.6% for the micro-anchored cables with $D_a = 3.6$ mm and 6.0 mm, respectively, as compared to the unanchored cable. This demonstrated that the use of micro-anchors can increase the interfacial bond between FO cable and soil and therefore extend the measurement range of a DFOS system (Hauswirth et al. 2010; Iten et al. 2011; Damiano et al. 2017).

**Behavior of Unanchored Cable–Sand Interface**

Prior to data analysis, the monitored strains along the 200 mm-long free cable segment were converted to tensile forces and compared with force gauge measurements (Fig. 10). There was generally good agreement between the two forces, indicating the validity of the measured strain data. Fig. 11 shows the obtained strain data (relative to the zero strain measurement) along the FO cables for each displacement step. Because the strain profiles exhibited no waviness, no signal processing procedure (e.g., filtering) was performed. In addition, temperature compensation for the measured strains was not considered as the variation of temperature was negligible during testing. For ease of comparison, the pullout force–displacement curves are shown in the upper right corner. The displacement steps are denoted as closed circles for the strain distributions presented and discussed.

For the unanchored FO cable, the strain propagated from the cable head toward the toe under increasing displacement steps (Fig. 11a). This indicated that initially only a small portion of ISS was mobilized to resist the pullout force; however, with the increase of the pullout force the ISS increased gradually in terms of both magnitude and mobilized length. Once the peak pullout force was reached (displacement step = 5 mm), the maximum strain began to decline,
indicating the decrease of the average ISS. To examine the evolution of ISS in detail, the pullout behavior of the unanchored FO cable in sand was further simulated using a pullout model incorporating strain-softening of the cable–soil interface (Zhang et al. 2014a). The correlation between pullout force and pullout displacement for five pullout phases (Phase I–V) can be expressed as (Zhang et al. 2014a):

\[
F_0 = \begin{cases} 
\frac{\pi D G_1 \tan \alpha_1 L}{\alpha_1} u_0 
\quad \text{(Phase I)} \\
\frac{\pi D G_2 \cot \alpha_2 L \tau_{\text{max}}}{\alpha_2 \tau_{\text{res}}} u_0 + \frac{\pi D \tau_{\text{max}}}{\alpha_2 \tau_{\text{res}}} -(1 + \frac{G_2}{G_1}) \frac{\pi D \cot \alpha_2 L \tau_{\text{max}}^2}{\alpha_2 \tau_{\text{res}}} 
\quad \text{(Phase II)} \\
-\frac{\pi D G_2 \tan \alpha_2 L}{\alpha_2} u_0 + (1 + \frac{G_2}{G_1}) \frac{\pi D \tan \alpha_2 L \tau_{\text{max}}}{\alpha_2} 
\quad \text{(Phase III)} \\
\frac{\pi D^2 E}{4L_2} u_0 + \frac{\pi D L \tau_{\text{res}}}{2} - \frac{\pi D^2 E}{4L_2} \left( \frac{\tau_{\text{max}}}{G_1} + \frac{\tau_{\text{max}}}{G_2} - \frac{\tau_{\text{res}}}{G_2} \right) 
\quad \text{(Phase IV)} \\
\pi D \tau_{\text{res}} L 
\quad \text{(Phase V)}
\end{cases}
\]

where \( D, L, \) and \( E \) = diameter, length, and Young’s modulus of the unanchored FO cable, respectively; \( L_s \) and \( L_r \) = lengths of softening and residual zones, respectively; \( G_1 \) and \( G_2 \) = cable–soil interfacial shear stiffnesses corresponding to ascending and descending branches, respectively; \( \tau_{\text{max}} \) and \( \tau_{\text{res}} \) = peak and residual cable–soil ISSs, respectively; and \( \alpha_i = \sqrt{4G_i/ED} \) \((i = 1, 2)\). The expression of axial strain and ISS distributions and further details of the model can be found in Zhang et al. (2014a).

The values of independent parameters for simulating the behavior of the unanchored FO cable during pullout are as follows: \( D = 2 \) mm; \( L = 1,200 \) mm; \( E = 0.34 \) GPa; \( G_1 = 3.00 \) MPa/m; \( G_2 = 55.83 \) kPa/m; \( \tau_{\text{max}} = 0.75 \) kPa; and \( \tau_{\text{res}} = 0.40 \) kPa. The simulated results are shown in Figs. 12a–c. Note that here the pullout force was calculated according to strain readings along the free cable segment. There was generally good agreement between the measured force–displacement curve and the simulated curve, except for the final residual phase where the measured force did not rigorously reach a constant value (Fig. 12a). Five pullout phases are also marked in the figure according to the simulation results. Prior to reaching the final residual
phase (Phase V), the percentage of displacement generated during each pullout phase (Phase I–
IV) was 3.04%, 37.18%, 39.15%, and 20.63%, respectively. The two transitional phases—
Phase II (elastic–softening phase) and Phase IV (softening–residual phase)—was significant,
further illustrating the progressive failure nature of the cable–soil interface. The distribution of
ISS along the FO cable was highly nonuniform (Fig. 12c). Initially, the ISS increased along the
whole length of the cable. Once the peak ISS was reached, the ISS began to decrease for the
segment close to the cable head, whereas that along the remaining segment continued to
increase. The ISS was fully mobilized when the peak pullout force was reached. Afterward, the
ISS along the whole length of the cable decreased toward the residual value ($\tau_{\text{res}} = 0.40$ kPa).

**Behavior of Anchored Cable–Sand Interface**

The pattern of strain profile for the micro-anchored cables was different from that of the
unanchored one (Figs. 11b and c). The former exhibited a unique step-like pattern due to the
addition of micro-anchors. The inclination of the strain curve of unanchored segments was
smaller than that of anchored segments, indicating that the ISS along the unanchored segments
was comparatively low. Moreover, although the average ISS over the whole length of the FO
cable increased sharply with increasing displacement steps, the variation of ISS along
individual segments (unanchored or anchored) appeared to be less significant. To the authors’
knowledge, no analytical model is available in the literature to reproduce such behavior as well
as the strain profiles shown in Figs. 11b and c. Therefore, the ISS along each segment was
estimated using:

$$\tau = -\frac{E_{\text{seg}} D_{\text{seg}}}{4} \frac{d\varepsilon}{dx}$$  \hspace{1cm} (4)

where $d\varepsilon/dx = $ axial strain gradient; and $E_{\text{seg}}$ and $D_{\text{seg}}$ = average Young’s modulus and
diameter of a particular segment, respectively. For the unanchored segments, linear fits were
used to obtain the slope of a curve; the average coefficients of determination ($R^2$) were 0.96 and
0.83 for the anchored cable with $D_a = 3.6$ mm and 6.0 mm, respectively. For each anchored
segment, the slope was regarded as the strain difference between two neighboring unanchored
segments divided by anchor length. For clarity, the unanchored segments are marked as A, B,
C, D, and E from left to right, whereas the anchored segments are marked as a, b, c, d, and e
(Figs. 11b and c). Note that the unanchored segment at the cable toe was neglected considering
its short length, and therefore the last anchored segment e was not considered as well. Finally,
the overall average ISS was estimated using $\tau = F_0 / \pi D L$, where $D$ = average diameter of the
FO cable.

The calculated ISSs are shown in Fig. 13. The overall average ISS over the whole cable
length increased gradually toward a constant value (Figs. 13a and d), consistent with the
correlation between the pullout force and the pullout displacement (Fig. 8). The unanchored
segments of the anchored FO cables exhibited strain-softening (cable with $D_a = 3.6$ mm in
particular; Figs. 13b and e), which was similar to the behavior of the unanchored FO cable.
However, the average ISS along the unanchored segments decreased toward 0.46 kPa (or 0.53
kPa) for the anchored cable with $D_a = 3.6$ mm (respectively, $D_a = 6.0$ mm), which was larger
than the residual ISS along the unanchored cable ($\tau_{res} = 0.40$ kPa).

Upon applying a pullout displacement, the ISS was simultaneously mobilized along the
unanchored segments (Figs. 13b and e) and the anchored segments (Figs. 13c and f). However,
as expected, the ISS along the unanchored segments was much smaller than that along the
anchored segments, demonstrating that the inclusion of micro-anchors led to the difference in
peak ISS (Fig. 9). Additionally, the average ISS along the unanchored segments peaked at a
displacement step of approximately 7 mm for the anchored cable, which was earlier than the
peak of average ISS along the anchored segments. The latter reached a peak value at the
displacement step being almost identical to that which resulted in the overall failure of the
anchored cables. The difference in average ISS between anchored and unanchored cable
segments of the micro-anchored FO cable was further characterized using their ratio, which is
defined as
where \( E_A a \) and \( E_A b \) = effective axial stiffnesses of the anchored and unanchored cable segments, respectively; and \( \bar{r}_a \) and \( \bar{r}_b \) = average ISSs along the anchored and unanchored cable segments, respectively. Fig. 14 shows the difference in average ISS between the anchored and unanchored segments calculated using eq. (4). The ratio increased approximately linearly with increasing displacement steps, further illustrating the contribution of anchored and unanchored segments to the ISS during pullout. For the contribution made by each micro-anchor, a close examination of Figs. 13c and f suggested that anchored segments close to the cable head contributed, in general, more to the ISS than those close to the toe. However, the ISS of anchored segment c became the largest after applying the displacement step of 9 mm (Fig. 13f). This could have occurred if this particular micro-anchor had a larger diameter and a rougher surface, as the property of each micro-anchor could not be strictly controlled during heat shrinking.

Discussion

Implications for Geotechnical Monitoring

The proper deployment of FO strain sensing cables is one of the major concerns in DFOS-based geotechnical monitoring (Damiano et al. 2017; Schenato 2017). This becomes extremely difficult to deal with natural geomaterials (e.g., soils) as compared to man-made materials. Accordingly, anchoring systems have been used by geotechnical practitioners to prevent the relative slippage between FO cable and soil (Hauswirth et al. 2010, 2014; Iten et al. 2011; Zhu et al. 2014; Damiano et al. 2017). Such a system has been preliminarily evaluated by using classical pullout tests in this paper. The obtained results indicate that the mechanical coupling between the strain sensing cable and the surrounding soil can be effectively enhanced (Fig. 9) with relatively little effort, that is, by shrinking commercially available heat-shrink tubes onto
the cable coating and therefore the equally spaced tubes can serve as a micro-anchorage system (Fig. 5b).

FO strain cables are usually point fixed (Pelecanos et al. 2018) or overall bonded (Shi et al. 2003) to a monitored object. Iten et al. (2011) proposed that a combination of overall bonding and point fixation is possible by using a soil-embedded micro-anchored FO cable, which is further confirmed by the development of ISS along the anchored and unanchored cable segments calculated from the high-resolution strain profiles (Fig. 13). The results reveal that the micro-anchored FO cable–soil contact is a combination of overall bonding and point fixation depending on the level of mobilized ISS, and therefore the validity of FO strain data is correlated to a three-stage process during the cable–soil interface failure (Fig. 15 and Table 4).

In Stage I, the cable is bonded along its entire length to the soil considering that neither the unanchored nor the anchored segment reaches the peak ISS. Since deformation compatibility between the cable and the soil is ensured, the strain measurements can truly reflect the soil deformation. In Stage II, the peak ISS of the unanchored segment is reached and therefore the anchors contribute a substantial part of the ISS. In this stage, the micro-anchored FO cable is similar to a gauged strainmeter and so the measured strain is averaged over the gauge length, namely, anchor spacing. Therefore, one has to carefully consider the anchor spacing so as not to compromise the spatial resolution of the DFOS system (Schenato 2017). Stage III follows when the anchors begin to fail provided that the cable itself has not yielded. The measured data are completely unreliable in this stage. In this section, the reliability of strain data measured from a micro-anchored FO cable has been linked to the progressive failure process of the cable–soil interface, but for field monitoring how to distinguish when the interface has transitioned from one stage to another remains to be investigated.

Limitations
The quality of distributed FO strain data is intrinsically influenced by its distributed nature. The measured strain is averaged over a certain length called spatial resolution, which has remarkably increased during the past few years to several millimeters for the optical frequency-domain reflectometry (OFDR) technology (Ni et al. 2018; Friedli et al. 2019). In this study a spatial resolution of 50 mm and a readout resolution of 10 mm were achieved by using BOTDA. Because this spatial resolution was two times the length of the micro-anchor (i.e., 25 mm, Fig. 5b), the quality of the obtained strain data along the anchored segments was therefore inevitably influenced. Moreover, similar to a geogrid the passive earth resistance produced against the micro-anchors should be an important component of the mobilized interaction mechanism between the anchored cable and the surrounding soil. This effect was, however, not fully considered in this preliminary study. Further research is needed to obtain a more accurate strain profile using advanced technologies such as OFDR and, hence, a refined analysis of the passive earth pressure effect can be performed.

Furthermore, although anchoring systems such as the one proposed in this study or by other researchers (e.g., Hauswirth et al. 2010) can effectively improve the cable–soil mechanical coupling, they do not allow lateral strains to be measured in a soil. In fact, it is a limitation of the DFOS technology that only strains along the longitudinal axis of a FO cable can be recorded. Therefore, the information a single FO cable can provide on the global strain state in a soil at a specific spatial location is limited.

**Conclusions**

In this study, the interaction between unanchored/micro-anchored FO strain cables and sand was investigated through laboratory pullout tests. High-resolution strain profiles along the FO cables during cable–soil interface failure were recorded by using the BOTDA technology. The strain profiles showed that both unanchored and micro-anchored FO cables exhibited remarkable progressive failure behavior in dry, loose sand during pullout. The unanchored
cable exhibited a strain-softening behavior, which was described by using an existing pullout model whereby the evolution of ISS was obtained. The simulated pullout force–displacement curves and strain distributions were generally in good agreement with measured curves. The micro-anchored cables had unique step-like strain profiles. The average ISS along the anchored segments were much higher than that along the unanchored segments; their ratio increased approximately linearly with increasing displacement steps. Moreover, the anchored segments close to the cable head contributed, in general, more to the ISS than those close to the toe.

Shrinking commercially available heat-shrink tubes onto the cable coating is a rapid, low-cost approach to make an anchored DFOS system for geotechnical monitoring. The inclusion of micro-anchors largely increased the peak ISS and hence the mechanical coupling between FO cable and soil, without significantly affecting the interfacial shear stiffness. The micro-anchored cable–soil contact is a combination of overall bonding and point fixation depending on the level of ISS. The validity of FO strain data is correlated to a three-stage process during the cable–soil interface failure: (1) the measured strain is valid when the cable is bonded along its entire length to the soil; (2) the measured strain is an average value over the gauge length when the unanchored segment fails and the cable is therefore point-fixed to the soil; and (3) the measured strain becomes unreliable once an overall interface failure occurs.

Acknowledgments
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**Notation list**

The following symbols are used in this paper:

- $A$ = cross-sectional area of fiber optic cable
- $C_c$ = curvature coefficient of soil
- $C_u$ = uniformity coefficient of soil
- $D$ = diameter of cable
- $D_{	ext{eff}}$ = effective grain size of soil
- $D_{50}$ = average grain size of soil
- $D_a$ = micro-anchor diameter
- $D_r$ = relative density of sand
- $D_{\text{seg}}$ = diameter of a particular cable segment
- $\bar{D}$ = average cable diameter
- $E$ = Young’s modulus of cable
- $E_a$ = Young’s modulus of anchored cable segment
- $E_b$ = Young’s modulus of unanchored cable segment
- $E_{\text{seg}}$ = Young’s modulus of a particular cable segment
- $F_0$ = pullout force
- $G_1$ = cable–soil interfacial shear stiffness corresponding to an ascending branch
- $G_2$ = cable–soil interfacial shear stiffness corresponding to a descending branch
- $G_s$ = specific gravity of soil
- $L$ = embedded cable length
- $L_s$ = length of softening zone
- $L_r$ = lengths of residual zone
- $T$ = temperature
- $u_0$ = pullout displacement
- $\alpha$ = pullout model coefficient
\[ \varepsilon = \text{axial cable strain} \]

\[ \nu_B = \text{Brillouin frequency shift after a measurement} \]

\[ \nu_{B0} = \text{Brillouin frequency shift before a measurement} \]

\[ \tau = \text{cable–soil interfacial shear stress (ISS)} \]

\[ \tau_{\text{max}} = \text{peak ISS} \]

\[ \tau_{\text{res}} = \text{residual ISS} \]

\[ \bar{\tau}_a = \text{average ISS along anchored cable segments} \]

\[ \bar{\tau}_b = \text{average ISS along unanchored cable segments} \]

\[ \varphi = \text{friction angle of soil} \]

**References**


Table 1. Physical and mechanical properties of the sand.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity $G_s$</td>
<td>—</td>
<td>2.67</td>
</tr>
<tr>
<td>Effective grain size $D_{10}$</td>
<td>mm</td>
<td>0.23</td>
</tr>
<tr>
<td>Average grain size $D_{50}$</td>
<td>mm</td>
<td>0.35</td>
</tr>
<tr>
<td>Coefficient of uniformity $C_u$</td>
<td>—</td>
<td>1.61</td>
</tr>
<tr>
<td>Coefficient of curvature $C_c$</td>
<td>—</td>
<td>1.06</td>
</tr>
<tr>
<td>Minimum dry density $\rho_{d_{\min}}$</td>
<td>g/cm$^3$</td>
<td>1.21</td>
</tr>
<tr>
<td>Maximum dry density $\rho_{d_{\max}}$</td>
<td>g/cm$^3$</td>
<td>1.69</td>
</tr>
<tr>
<td>Friction angle $\phi$</td>
<td>°</td>
<td>32.3</td>
</tr>
</tbody>
</table>
Table 2. Properties of the tight-buffed single-mode fiber optic (FO) strain cable.

<table>
<thead>
<tr>
<th>Coating material</th>
<th>Outer diameter (mm)</th>
<th>Average Young’s modulus (GPa)</th>
<th>Unit weight (kg/km)</th>
<th>Tensile strength (MPa)</th>
<th>Effective axial stiffness (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane</td>
<td>0.9</td>
<td>2.0</td>
<td>0.34</td>
<td>4.1</td>
<td>23.1</td>
</tr>
</tbody>
</table>

\(^a\) Determined under a tensile strain of 1\%. 
Table 3. Properties of two types of micro-anchor.

<table>
<thead>
<tr>
<th>Material</th>
<th>Length (mm)</th>
<th>Spacing (mm)</th>
<th>Diameter (mm)</th>
<th>Average Young’s modulus of anchored segment (GPa)&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Average diameter of cable (mm)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE tube&lt;sup&gt;c&lt;/sup&gt;</td>
<td>25</td>
<td>250</td>
<td>3.6</td>
<td>0.78</td>
<td>2.17</td>
</tr>
<tr>
<td>PMMA tube&lt;sup&gt;d&lt;/sup&gt;</td>
<td>25</td>
<td>250</td>
<td>6.0</td>
<td>2.70</td>
<td>2.42</td>
</tr>
</tbody>
</table>

<sup>a</sup>Calculated based on cross-section geometry.

<sup>b</sup>Calculated based on micro-anchor distribution.

<sup>c</sup>PE = polyethylene.

<sup>d</sup>PMMA = polymethyl methacrylate.
Table 4. Validity of FO strain data related to a three-stage process of the cable–soil interface failure.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Peak ISS of unanchored segment reached or not(^a)</th>
<th>Peak ISS of anchored segment reached or not</th>
<th>Coupling condition</th>
<th>FO strain data</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>No</td>
<td>No</td>
<td>Overall bonding</td>
<td>Valid</td>
</tr>
<tr>
<td>II</td>
<td>Yes</td>
<td>No</td>
<td>Point fixation(^b)</td>
<td>Averaged over gauge length(^c)</td>
</tr>
<tr>
<td>III</td>
<td>Yes</td>
<td>Yes(^d)</td>
<td>Decoupling</td>
<td>Invalid</td>
</tr>
</tbody>
</table>

\(^a\)ISS = interfacial shear stress.

\(^b\)The micro-anchored FO cable is similar to a gauged strainmeter.

\(^c\)The gauge length is equivalent to anchor spacing.

\(^d\)Provided that the cable itself has not yielded.
**Figure captions**

**Fig. 1.** Schematic diagram of ground deformation sensing using a micro-anchored fiber optic (FO) strain cable.

**Fig. 2.** (a) Distributions of axial force and interfacial shear stress (ISS) along an unanchored soil inclusion during pullout at the critical state; and (b) hypothesized axial force and ISS distributions for an anchored soil inclusion.

**Fig. 3.** Schematic of the principle of distributed fiber optic sensing (DFOS) using Brillouin optical time-domain analysis (BOTDA).

**Fig. 4.** Grain size distribution curve of the soil.

**Fig. 5.** (a) Structure of the FO cable; and (b) layout of micro-anchors on the FO cable (unit: mm).

**Fig. 6.** Schematic of the test setup (unit: mm; not to scale).

**Fig. 7.** Schematic of the clamp used to clamp the FO cable (unit: mm; not to scale).

**Fig. 8.** Experimental curves of pullout force versus pullout displacement under different micro-anchor diameters.

**Fig. 9.** Influence of micro-anchor on the secant interfacial shear stiffness and peak ISS. The secant interfacial shear stiffness was determined under a displacement step of 2 mm.

**Fig. 10.** Comparison between pullout forces measured by the force gauge and those calculated using FO strain measurements.

**Fig. 11.** Strain profiles along the FO cables captured using BOTDA during the progressive failure of the cable–soil interface: (a) unanchored FO cable; (b) micro-anchored FO cable ($D_a = 3.6$ mm); and (c) micro-anchored FO cable ($D_a = 6.0$ mm).

**Fig. 12.** Simulated results for the unanchored FO cable: (a) pullout force–displacement curve; (b) strain profiles; and (c) ISS profiles. Five pullout phases are marked in (a) according to the simulation results.
Fig. 13. Overall average ISS and ISS along unanchored and anchored segments for the micro-
anchored FO cable with: (a–c) $D_a = 3.6$ mm; and (d–f) $D_a = 6.0$ mm.

Fig. 14. Difference of average ISS between anchored and unanchored segments of the micro-
anchored FO cables.

Fig. 15. Validity of FO strain data as related to a three-stage process of the cable–soil interface
failure. The unanchored segment B and two neighboring anchored segments a and b for the
micro-anchored FO cable with $D_a = 6.0$ mm are taken as an instance.
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