FIBER OPTIC BASED INCLINOMETER FOR REMOTE MONITORING OF LANDSLIDES: ON SITE COMPARISON WITH TRADITIONAL INCLINOMETERS

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ABSTRACT

Distributed optical fiber sensors, and in particular those based on stimulated Brillouin scattering, have in recent years been the object of a growing attention for structural and environmental monitoring of large areas because they allow to measure strain and temperature profiles up to tens of kilometers with a strain accuracy of ±10µε and a temperature accuracy of ±1°C. In this paper, we present the application of the above sensing principle to the realization and field testing of a novel inclinometer for the measurement of 3D deformation of soil.

Index Terms— Optical fiber sensors, SBS, BOTDA

1. INTRODUCTION

In recent years, optical fiber sensors have gained considerable attention in structural and environmental monitoring due to a definite number of advantages including the immunity to electromagnetic interferences, the high sensitivity, the small size and the multiplexing and remote interrogation capabilities [1]. In particular, distributed optical fiber sensors based on stimulated Brillouin scattering (SBS) allow, through the so-called Brillouin Optical Time Domain Analysis (BOTDA), to measure strain and temperature profiles by means of a telecommunications grade optical fiber cable for very long distances, up to tens of kilometers [2, 3]. They have been successfully employed in the monitoring of large civil and geotechnical structures such as bridges, tunnels, dams, pipelines allowing to identify and localize any kind of failures that can occur during their construction and operation [4–6]. A novel inclinometer, exploiting SBS based distributed optical fiber sensors, has been devised and realized. Its main characteristics can be summarized as follows: (a) measurement of 3D deformation of soil; (b) continuous monitoring from a remote site and multiplexing capability; (c) self-compensation against temperature variations; (d) displacement sensitivity as high as 1 mm over 1 m; (e) safe operation up to overall displacements as large as 15 cm over 1 m, the limit being posed just by the breaking of the sensing optical fiber. It should be emphasized that the above characteristics are not fulfilled by traditional inclinometers which usually require periodic inspections for interrogation, and become useless if the displacement reaches values as large as to prevent the sliding of the measuring head along the inclinometer tube itself (a few cm of movement across a narrow slip plane). Experimental results relative to the exploitation of the proposed fiber optic inclinometer to monitor an actual slope, along with the comparison with traditional inclinometers readings, are presented.

2. BASICS OF SBS DISTRIBUTED OPTICAL FIBER SENSORS

Stimulated Brillouin scattering is a non-linear process occurring in optical fibers at relatively low power levels and gives rise to the conversion of a small fraction of the incident power to backscattered light at a lower frequency [7]. Brillouin scattering arises from acoustic waves guided in the optical fiber. When a pump wave and a frequency down-shifted counter-propagating probe wave are simultaneously injected into the fiber, their interference generates an acoustic wave through electrostriction, and the Bragg diffraction induced by the acoustic wave subsequently scatters the pump wave into the probe wave. Maximum probe gain occurs for a precise value of the pump-probe frequency shift, named Brillouin frequency shift, which depends on the strain and the temperature of the optical fiber [8]. BOTDA is a method that generates Brillouin gain at a specified location along the optical fiber, by pulsing the intensity of the pump wave. Probe amplification is recorded as a function of time, since the instant of launch of the pulsed pump, for a selected numbers of pump-probe
frequency shifts. Acquisition time is then converted in fiber locations, by using the group velocity of the optical pump. Standard BOTDA method offers good accuracy and long sensing range.

### 3. OPTICAL FIBER BASED INCLINOMETER

The optical fiber inclinometer is realized by gluing, using epoxy adhesive, four equally spaced fibers along the sides of a PVC pipe for its entire length, as shown in Fig. 1.

![Figure 1 The optical fiber inclinometer tube](image)

The pipe diameter is 50 mm, with a thickness of 3.2 mm, while its overall length is 750 cm, achieved by connecting three pipe sections of 250 cm. The measurement of the strain profiles along the fibers allows the reconstruction of the 3-D deformation of the pipe and, consequently, the movements of the soil where the pipe is embedded in. It is important to underline that the proposed device is different from the optical fiber inclinometer recently proposed in [9], where point sensors, namely fiber Bragg gratings, have been employed.

In brief, the method is based on the integration of the bending moments extracted from the strain profiles provided by the four optical fibers. According to the Euler-Bernoulli beam theory, the normal strain along any cross-section \( z \) of the pipeline is represented by the following linear relation [10]:

\[
\varepsilon(x, y, z) = a(z)x + b(z)y + c(z)
\]  

(1)

At each pipe position \( z \), the BOTDA sensor provides the strain at the four coordinates indicated in Fig. 1. Therefore, Eq. (1) can be used to build a system of four linear equations in the three variables \( a, b \) and \( c \). It is important to underline that, while three fibers would be sufficient to reconstruct pipe deformation [5], the introduction of the fourth fiber allows for larger precision in strain plane (and therefore displacement) computation, by application of a least-square best fitting procedure in determining \( a, b \) and \( c \).

From the strain distribution, one can calculate the bending moment components along the \( x \)- and the \( y \)-direction, for each fixed abscissa \( z \):

\[
M_x(z) = \int_A \left( E\varepsilon(x, y, z) \right)_y dA
\]  

(2a)

\[
M_y(z) = -\int_A \left( E\varepsilon(x, y, z) \right)_x dA
\]  

(2b)

where \( E \) represents the Young’s modulus of the pipe’s material, and the integrals extend over the pipe’s cross-section. The \( x \)- and \( y \)-components of the displacement at each section are finally retrieved by integrating the following differential equation representing the equilibrium condition for the beam [10]:

\[
M_y(z) = -EI \cdot u'_x(z) \quad (3a)
\]

\[
M_x(z) = -EI \cdot u'_y(z) \quad (3b)
\]

where the prime ‘ denotes derivation with respect to \( z \), and \( I \) represents the pipe moment of inertia. For the beam geometry considered in this work, we have:

\[
I = \frac{\pi}{4} \left( R_{ext}^4 - R_{int}^4 \right) \quad (4)
\]

where \( R_{ext} \) and \( R_{int} \) are the outer and the inner radii of the pipe, respectively. Integration of Eqs. (3) requires the use of proper boundary conditions. In the experimental tests reported below, integrations were performed assuming that one pipe end was anchored so that to establish a full momentum connection, i.e. both displacement and its first derivative are null at \( z = 0 \).

It is interesting to observe that the described method is tolerant with respect to temperature gradients along the borehole, as long as the temperature is the same at each cross section of the instrumented pipe. In fact, while uncompensated temperature gradients along the borehole alter the strain profile measurements due to the intrinsic sensitivity of the Brillouin frequency shift to temperature and strain, the computation of pipe displacement at any section is not affected by these temperature-induced offsets. This can be easily demonstrated by noting that, any offset in the strain distribution described by Eq. (1) only changes the \( c \) parameter, which is irrelevant when computing the bending moment components by use of Eqs (2). In other words, the bending moments provided by Eqs. (2) are independent of any constant added to the strain distribution.

In order to assess the validity of the proposed approach, several laboratory tests were performed on the inclinometer tube before the on-site installation. We show in Fig. 2 a selection of the results achieved during the laboratory tests. In detail, we show the vertical displacement along a 180 cm-long pipe, with identical cross-section of the pipe used on-site, subjected to prescribed displacement at one end and fixed on the other end. The displacements retrieved by the
optical fiber sensors are compared to the ones provided by eight dial gauges distributed along the pipe. It is seen that the agreement is remarkably good, at least for vertical displacements of the free end as large as 15 mm. For larger displacements, some underestimation of the displacements provided by the optical fiber sensors is noted. In particular, the maximum deviation between the dial gauge and optical fiber displacement was about 5 mm, corresponding to a discrepancy of about 15%. Such a discrepancy can be partly attributed to the difficulty, during experiments, to keep the deformed pipe perfectly vertical, especially for larger displacements. That results in a y-component of the displacement read by the optical fiber smaller than the total displacement provided by the dial gauge. Another source of discrepancy may be the deformation of the pipe cross-section, which is not taken into account into the model employed to retrieve the displacements from the strain in case of optical fiber measurements.

\[
\begin{align*}
\delta_{\text{FOI-S9F}} & = 4.04 \text{ mm} \\
\delta_{\text{I9B}} & = 12.1 \text{ mm} \\
\delta_{\text{I9C}} & = 15.9 \text{ mm} \\
\delta_{\text{I9F}} & = 29.3 \text{ mm} \\
\delta_{\text{I9F}} & = 35.7 \text{ mm}
\end{align*}
\]

Figure 2 Comparison between the displacements provided by the optical fiber sensor (solid lines) and the ones provided by the dial gauges (squares).

4. ON-SITE MEASUREMENT RESULTS

The selected test site was an area, located in Basilicata Region (Italy), subject to slow soil movements and already instrumented with traditional inclinometer tubes. The test site is depicted in Fig. 2, where the positions of the traditional inclinometers and the fiber optic one are shown, as well.

The optical fiber inclinometer was installed in a 750 cm deep borehole which was then filled with grout. After allowing the grout cure for one month, a first measurement was performed as a reference in order to eliminate all the strain induced by the installation procedure. The subsequent measurements allow the detection of any soil movements. Figure 4 shows the obtained results.

The data provided by the inclinometer I9B suggest that the land displacement occurred down to a maximum depth of about 12 meters. Unfortunately, this is larger than the length of our optical fiber inclinometer. Therefore, the assumption of zero displacement at the bottom of optical fiber inclinometer cannot be considered valid. However, despite its limited length, the fiber optical inclinometer exhibits a sufficient accuracy in detecting the maximum pipe displacement at the ground surface.

5. CONCLUSIONS

An optical fiber BOTDA based inclinometer has been devised, laboratory tested and on-site installed. The preliminary results show a good agreement with traditional inclinometers readings. The small observed differences can be attributed to the non perfect co-location of the devices and to the usual differences, always present also when traditional inclinometers are installed with different grout mixes. The proposed device can, therefore, be regarded as a valid alternative to traditional inclinometers, offering the
possibility of a wider displacement range and the remote interrogation of multiple devices with permanent monitoring ability.

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7. REFERENCES