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Brillouin optical time-domain analysis for geotechnical monitoring

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ABSTRACT

In this paper, we show some recent experimental applications of Brillouin optical time-domain analysis (BOTDA) based sensors for geotechnical monitoring. In particular, how these sensors can be applied to detecting early movements of soil slopes by the direct embedding of suitable fiber cables in the ground is presented. Furthermore, the same technology can be used to realize innovative inclinometers, as well as smart foundation anchors.

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1. Introduction

Distributed fiber-optic strain sensors have great potentialities in the field of geotechnical monitoring (Dewynter et al., 2009; Olivares et al., 2009; Iten, 2011; Minardo et al., 2014). By integrating a single fiber-optic cable into soil or a geotechnical work, a large number of accurate, spatially resolved data can be obtained. The Brillouin optical time-domain analysis (BOTDA) method allows for strain measurements in the microstrain range, with a typical spatial resolution of 1 m and a maximum sensing range of 50 km. This means that thousands of "strain gauges" along a single cable connected to structures, embedded in soil or grouted into boreholes, for example, can provide information about the current state of the object under supervision. The objects can include geological and civil structures, such as a construction site, a tunnel, a landslide prone area, or a pipeline. It is evident that such a technology implies a benefit for placing fiber-optic cables anywhere possible on construction sites and in the green field (Minardo et al., 2012).

This paper summarizes some results of experiments carried out by research staff at Second University of Naples. In particular, after a brief description of the sensor technology, three applications of the BOTDA technology in the geotechnical field will be described: (a) slope monitoring by optical fibers embedded into the soil; (b) detection of soil movement by use of an optical fiber based inclinometer; (c) monitoring of a ground anchor by use of an embedded optical fiber.

2. Principle of operation of BOTDA

The experimental results reported in this paper have been conducted exploiting stimulated Brillouin scattering (Boyd, 2008) in single-mode optical fibers. In brief, two counter-propagating lightwaves exchange energy along the fiber, in a measure depending on their frequency offset. If the offset falls within a specific range, the radiation at higher frequency (pump wave) transfers energy to that at lower frequency (Stokes wave). The sensing principle is based on the fact that the frequency difference at which the maximum amplification of the Stokes wave occurs, known as Brillouin frequency shift (BFS), varies depending on the mechanical and thermal states of the fiber. In particular, the BFS increases with both temperature and strain. Spatial resolution, i.e. the ability to measure deformation and temperature changes in a distributed way, can be achieved through the use of a pulsed pump beam: in this way, the interaction takes place along successive sections of the fiber as the pump pulse propagates down the sensing cable. By recording the intensity of the Stokes radiation as a function of time, the Brillouin gain can be traced in each section. The measurement of the Brillouin gain as a function of time and frequency allows the entire profile of

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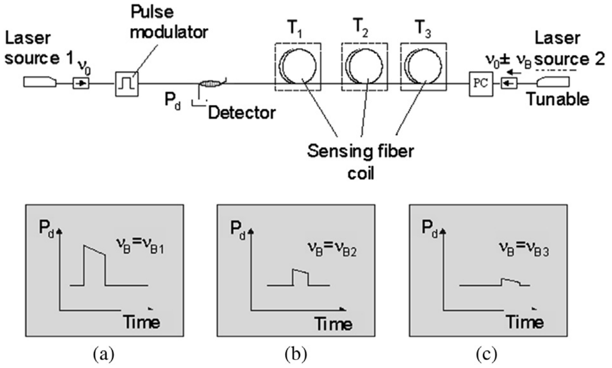

Fig. 1. Basic configuration for BOTDA: (a), (b) and (c) show the waveform of optical power at detector (P_d), acquired when the frequency offset between the two lasers is tuned to the Brillouin frequency shift ν_B of fiber coils 1, 2 and 3, placed at temperatures T_1, T_2 and T_3, respectively.

Brillouin shift along the fiber to be obtained, which in turn can be translated in terms of deformation or temperature through the use of appropriate calibration coefficients.

Fig. 1 shows the basic configuration employed for BOTDA. The pulsed and continuous wave (CW) beams are generated by two separated sources having lasing frequencies ν_0 and $\nu_0 \pm \nu_B$, shifted by a definite quantity in the range of the Brillouin frequency shift of the sensing fiber. Fig. 1 shows that the amplification of the Stokes beam occurs at those locations where the frequency offset with the crossing pulse matches the local Brillouin frequency shift, which in turn is related to the temperature (or strain) of the analyzed fiber coil. More in general, Brillouin time-domain signals are acquired in BOTDA systems for a range of frequency offsets, so as to get a full picture of the Brillouin frequency shift at each location.

3. Experiments on small-scale model slopes

The main requirements of monitoring systems in areas susceptible to sudden and rapid landslides should be the following: (a) a cheap and reliable instrumentation; (b) continuous monitoring in time and space; (c) low probability of error to avoid false or missed alarms.

For their ability to measure strain with spatial continuity, optical fibers are particularly attractive. For this reason, we decided to check their performance in the monitoring of slopes in loose unsaturated granular soils susceptible to catastrophic rainfall-induced flowslides. The basic idea is that a sensing fiber buried in the soil can detect the deformation due to ongoing volumetric and/or shear strains induced by the decrease in suction, which can be interpreted as a warning of incoming failure. The capability of the fiber to provide distributed strain readings should allow to detect ongoing deformation at any point of even very long slope sections. This is a fundamental advantage with respect to conventional monitoring devices (topographic readings, inclinometers, etc.) which can provide information only at specific points. The low cost of fibers is another relevant advantage.

This simple idea suggested an experimental program to test this new kind of sensors in small-scale model slopes subjected to artificial rainfall. The slopes are made of volcanic ash laid down into a flume imposing the same porosity as in the field. The water infiltration induced by artificial rain causes an increase in the water content and a decrease in suction and, consequently, volumetric and shear strains; this mechanical process can lead to slope failure. The basic equipment for monitoring includes tensiometers, pore pressure transducers, laser displacement transducers, electrical moisture probes (TDRs) and video-cameras (see Fig. 2). For the present application the flume was tilted with an inclination of 40°, and equipped with tensiometers, displacement sensors and optical fibers. The latter was a tight-buffer standard single-mode fiber for telecommunications having an overall diameter of 900 μm. The optical fiber sensor was buried into the ground along two alignments parallel to each other (Fig. 2). The model slopes, as a proof of principle, have been made up with volcanic ashes taken from the site of Cervinara, Italy, where field monitoring is being carried out (Pirone et al., 2012). The slope has a length of 1.35 m, thickness of 10 cm, initial water content ranging between 43% and 50%, and porosity close to the field value (70%–76%).

In the experiment, a system of anchoring constituted by small plastic grids glued every 20 cm at the fiber was adopted, as shown

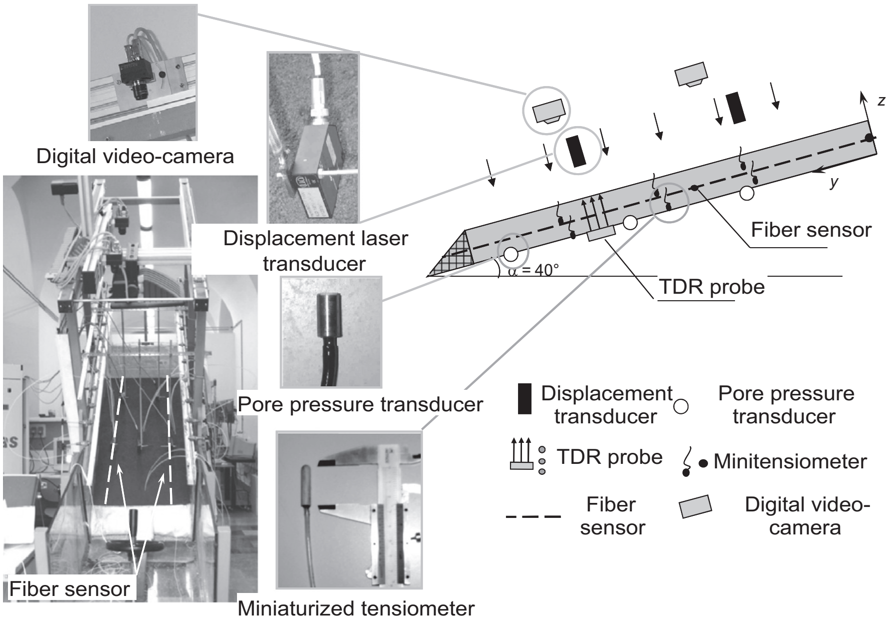

Fig. 2. The instrumented flume.

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