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Application of a high resolution distributed temperature sensor in a physical model reproducing subsurface water flow

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ABSTRACT

A distributed temperature optical fiber sensor system with a sub-centimeter spatial resolution has been incorporated in a sand-box model at the aim of investigating the variations induced by internal erosion on the temperature distribution in a dike. In particular, the laboratory investigation aims at studying the spatial distribution of the temperature variations occurring in the surroundings of an erosion channel (*pipe*). The calibration of the setup consisted in measuring the thermal response of an intact sample to a horizontal flow, with the inflowing water maintained at a constant temperature higher than the room temperature. No erosion occurred in the calibration test. The results of the calibration are presented in this paper and show that with the sensing system adopted temperature mapping in a soil sample can be obtained with such a richness of detail which is not comparable with that achieved adopting a system of pointwise sensors.

1. Introduction

Over the last 25 years fiber optic sensor (FOS)[1] technology has become an established sensing tool in several fields of application; about the use of fiber optics as sensors, very few know that the proposal of optical fibers as sensing elements is almost as old as their use as transmission media [1]. Several review papers, have described the many advantages FOSs offer with respect to legacy electronic sensors ([2,3] and therein references).

Coming to applications with high demanding requirements – large number of sensing points, harsh environments and large areas to cover – features as reliability, immunity to electromagnetic interference, cheapness of the sensing element, low operating cost, flexibility, easiness of multiplexing make FOSs a very appropriate, if not the only applicable, technological platform [4,5]. Geoenvironmental applications are among the most representative cases: having initially penetrated oil and gas industry, fiber optic sensors are nowadays available, also commercially, as viable replacement of most standard legacy sensors used in geotechnical and environmental engineering.

Among the others, a particular class of fiber optic sensors, the distributed FOSs (DFOSs)[2], represents the most promising class of sensors in the scenario of geoenvironmental monitoring, because of their unique feature, i.e. the ability of distributedly mapping the field of the measured physical quantity along the fiber. Furthermore, they represent a revolutionary tool for small and medium scale

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[1] FOS: Fiber Optic Sensor.

[2] DFOS: Distributed Fiber Optic Sensor.

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physical modelling, as they allow a terrific spatial resolution to be achieved – at centimeter scale or even less – with few tens of seconds of sampling time. The time required by the fiber to adapt to temperature changes is compatible with such short sampling time: it is demonstrated that a stainless-steel housed fiber adapts in less 15 s [6]. With this respect, the use of DFOSs enables better insight and more accurate modelling of investigated phenomena.

In this work we apply DFOSs to measure the spatio-temporal evolution of temperature within a *sand box model*. Such a sensing platform is usually referred to as Distributed Temperature Sensing (DTS); some examples of DTS[3] for geoenvironmental applications can be found in the literature [7].

Sand box models are used to observe phenomena as they actually occur in porous media. A common application is the modelling of groundwater flow at small or medium scale [8]. A sand box consists of a rigid, watertight container filled with a porous material and one or more fluids. Measuring devices and a supply system that reproduces the boundary conditions of the natural reservoir complete the model. The sand box described in this work reproduces in small scale the foundation layer of a water retaining structure. It is aimed at studying the spatial distribution of the temperature variations occurring in the surroundings of an erosion channel. The final aim of the research, that also includes numerical modelling and large-scale modelling, is studying the applicability of DTS to detect internal erosion under water retaining structures, with a particular focus on river embankments.

2. Distributed temperature sensing by fiber optics

As mentioned above, distributed measurement capability is singular of FOS technology, with no counterpart among standard legacy sensors. Generally speaking, the predictable behavior of the backscattered light generated by elastic and inelastic interactions between incident light and the material of the fiber itself under perturbation is at the basis of any DFOSs. Those interactions are based on three fundamental processes: Rayleigh, Raman and Brillouin scattering [9]. Each of these scattering processes generates a light pulse which propagates back to the input end when a proper input signal is injected into the fiber. Conditions of the environment surrounding the fiber influence the three processes as well as the generated backpropagating light. This is at the basis of the sensing mechanism, as the backscattered light is measured to sense local environment parameters along the fiber whilst the distributed feature is achieved by measuring the time delay, which separates forward and back-propagating light pulse [10]. All of the aforementioned scattering process are suitable to be used in distributed temperature sensing, but as it will be explained in the following, only Rayleigh based DTS are viable solutions to be deployed in small scale physical models.

About Raman scattering, measurement is possible by exploiting the intrinsic dependence of the intensity of (anti-Stokes) Raman scattering signal on the temperature along the fiber [11]. Due to this relatively simple mechanism, Raman based DTSs have been the first temperature DFOSs commercially available and represent, up to now, the most popular distributed temperature fiber optic sensors platform. Raman DTSs are characterized by spatial resolution up to 1 m, temperature resolution of 0.01 °C and spatial range up to tens of kilometers. These features make Raman DTSs effective in real-time monitoring of seepage streams in embankment, catchments and lakes [7].

Instead of intensity, in Brillouin scattering, it is the wavelength of the backscattered signal which is affected by the surrounding environment, through the local density of the fiber, which is ultimately determined by temperature and strain conditions [12]. Thus, Brillouin based DFOSs are viable for measuring both temperature and strain and, with proper transducing mechanisms, can be configured as displacement, force and pressure sensors. Nowadays, Brillouin based systems are available commercially and the commercial systems claim accuracy of 2 $\mu\varepsilon$ or less, for strain and less than 0.1 °C for temperature; about range and spatial resolution, they are capable of performing measurements over few tens of kilometers, with 0.5 m or slightly lower resolution. In particular, Brillouin-based sensor systems are preferably used in conjunction with Raman based systems so as to measure both temperature and strain, simultaneously. If it is not the case, proper approaches has to be adopted to face the cross-sensitivity of Brillouin to both temperature and strain.

Intensity, frequency, phase and polarization of Rayleigh scattering signal in fiber optics is on the contrary intrinsically independent of almost any external perturbation. The sensing is still possible because in Rayleigh-based DFOSs a different mechanism is exploited: sensing is enabled by any propagation effect, the backscattered light experiences while travelling back into the fiber, among which attenuation, phase interference and polarization rotation [13]. Those effects allow for the backscattered light to keep memory and encode any change in the surrounding environment. An important peculiar feature of Rayleigh based DOFS is that they cannot provide absolute strain/temperature, but only the variation with respect to an initial condition, assumed as reference. To this extent, commercially available Rayleigh-based sensing systems are directly capable of measuring temperature and strain variations, with 0.1 °C and 1 $\mu\varepsilon$ resolution, respectively. Range is in the order of some tens of meters, with a sub-centimeter spatial resolution. With those specifications (in particular with reference to the spatial resolution), Rayleigh DTS is the only one among the three platforms described above which is viable to be used inside a physical model at sub-meter scale as the model addressed here.

In particular, in this work an Optical Backscatter Reflectometer (OBR) from Luna™ has been used to interrogate a standard telecom 0.9 mm tight fiber cable. This device is a high resolution optical-frequency domain reflectometer, that measures the spectral shift in the local Rayleigh backscatter pattern. The spectral shift is temperature and strain dependent so that the knowledge of the temperature and strain coefficient of the used cable allows to calculate the local temperature and strain variation. Like for

[3] DTS: Distributed Temperature Sensing.

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