20th IMEKO TC4 International Symposium and
18th International Workshop on ADC Modelling and Testing
Research on Electric and Electronic Measurement for the Economic Upturn
Benevento, Italy, September 15-17, 2014

Application of a high resolution Distributed Temperature Sensor in a physical model reproducing subsurface water flow

Silvia Bersan[1] Luca Schenato[2], Aneesh Rajendran[3], Luca Palmieri[3], Simonetta Cola[1], Alessandro Pasuto[2], Paolo Simonini[1]

[1] Department of Civil, Environmental and Architectural Engineering, University of Padova, 35131 Padova, Italy, silvia.bersan@dicea.unipd.it
[2]Research Institute for Geo-Hydrological Protection, National Research Council of Italy, 35127 Padova, Italy, luca.schenato@cnr.it
[3]Department of Information Engineering, University of Padova, 35131 Padova, Italy, luca.palmieri@unipd.it

Abstract **– A distributed temperature optical fibre sensors system with a sub-centimetre spatial resolution has been incorporated in a sand-box model. Its function is monitoring the temperature field induced in the sand by a horizontal water flow with inflowing water maintained at a constant temperature higher than the room temperature. The setup has been designed to investigate the variations of the temperature field induced by internal erosion in a dike. The paper presents preliminary results concerning heat transfer in the intact sample, before internal erosion is triggered. The results 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.**

I. INTRODUCTION

Over the last 25 years fibre optic sensor (FOS) technology has become an established sensing tool in several fields of application; about the use of fibre optics as sensors, very few know that the proposal of optical fibres 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, fibre 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 fibre optic sensors, the distributed FOSs (DFOSs), 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 fibre. Furthermore, they represent a revolutionary tool for small and medium scale physical modelling, as they allow a terrific spatial resolution to be achieved - at centimetre scale or even less - with few tens of seconds of sampling time. 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 for geoenvironmental applications can be found in the literature [6].

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 [7]. 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. The aim of the work is studying the applicability of DTS to detect internal erosion under water retaining structures, with a particular focus on river embankments.

ISBN-14: 978-92-990073-2-7

II. DISTRIBUTED TEMPERATURE SENSING BY FIBRE OPTICS

As mentioned above, distributed measurement capability is singular of FOS technology, with no counterpart among standard legacy sensors. Generally speaking, the predictable behaviour of the backscattered light generated by elastic and inelastic interactions between incident light and the material of the fibre itself under perturbation is at the basis of any DFOSs. Those interactions are based on three fundamental processes: Rayleigh, Raman and Brillouin scattering [8]. 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 fibre. Conditions of the environment surrounding the fibre 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 fibre whilst the distributed feature is achieved by measuring the time delay which separates forward and back-propagating light pulse [9]. 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 fibre [10]. 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 fibre 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 kilometres. These features make Raman DTSs effective in real-time monitoring of seepage streams in embankment, catchments and lakes [6].

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 fibre, which is ultimately determined by temperature and strain conditions [11]. 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 με 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 kilometres, 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 fibre 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 fibre, among which attenuation, phase interference and polarization rotation [12]. 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 με resolution, respectively. Range is in the order of some tens of meters, with an impressive sub-centimetre 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 fibre 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 Brillouin systems, the cross-sensitivity of temperature and strain has to be conveniently faced and, in the case under investigation, all the possible sources of strain have been considered to correctly interpret the data.

III. DISTRIBUTED TEMPERATURE SENSING FOR PIPING DETECTION

Water retaining structures which lay on pervious and erodible soils are prone to *backward erosion piping,* the progressive removal of soil particles due to seepage forces, which can eventually lead the structure to collapse [13]. Despite not many cases of piping-induced collapse have been documented in dikes, due to the difficulty in recognizing clearly the traces of the mechanism before and even after the collapse occurred, piping is nowadays considered a big threat [14,15].

The highly localized nature of the process in its initial phase makes its detection difficult if traditional monitoring techniques, based on pointwise sensors, are employed. For instance a pore pressure monitoring system would require a maximum spacing among sensors of 2-3 m to be effective [16,17]. Researchers have therefore focused on finding other physical quantities related to seepage flow which were measurable by means of extensive techniques. Besides temperature, the suitability of infrared emissivity, electrical resistivity and self-potential is under study.

First studies on DTS as a tool to detect internal erosion date back to the nineties and optical fibres are now installed at several dam sites in Sweden, Germany, France, Turkey, China and Canada [18].

The functioning principle is based on the fact that, if an initial temperature difference exists between the inflowing water and the soil, the increase of flow velocity in the erosion channel and its surroundings generates variations in the temperature field of the embankment.

Although DTS looks promising for detection of backward erosion piping occurring in dikes, the dependence of temperature on a number of factors other than water fluxes and the little extent of the temperature anomalies induced by piping make detection not straightforward. In recent years research has focused on the development of advanced data analysis techniques able to separate temperature anomalies linked to leakages from temperature variations induced by other phenomena [19,20,21]. The validity of these techniques has been tested in instrumented sites mainly located along intake channels. Moreover, distributed temperature sensors have been installed in test dikes which have been brought to collapse by piping [22,23,17].

The sand box model presented in this work aims at giving insight in the physical process of heat transfer occurring under a dike affected by backward erosion piping.

IV. MODEL DESCRIPTION AND PRELIMINARY RESULTS

The sand box model reproduces in detail the model designed by van Beek et al. [23] for improving and validating the piping law adopted by the Dutch code. This similarity provides us with a reference for the test results regarding sand transport, so that we can mainly focus on the novel aspect of the problem: heat transfer.

We present here preliminary results obtained inducing a horizontal flow in a homogeneous sample where no internal erosion occurred.

The sample was 30 cm wide, 15 cm tall and 35 cm long in the direction of the flow. The sample was produced by wet deposition of uniform medium sand (d_{50} = 0.3 mm, C_u = 1.5) and compacted by shock waves to a relative density of around 90%. The optical fibre was embedded in the sand so that 15 measuring lines orthogonal to the flow direction have been arranged in three layers of five lines each. Four resistive platinum sensors (PT-100) measured the temperature of the inflowing and outflowing water as well as the temperature in the sand at two positions close to the fibre, thus providing an absolute temperature reference.

The test consisted in flushing the sample with water maintained at a constant temperature 10 °C higher than the room temperature. The flow was induced maintaining a constant head difference between inlet and outlet. Five piezometer tubes inserted into one of the lateral walls allowed to verify the effective hydraulic load applied to the sample and the trend of the hydraulic head inside the sample. The average Darcy velocity during the experiment was $9.5 \cdot 10^{-5}$ m/s. A sketch of the setup is given in figure 1.

Figure 2 shows the normalized frequency shift measured by the fibre after 4 hours from the beginning of the test. In the preliminary results presented here, the frequency shift is normalized by the maximum shift registered during the test; indeed, the temperature coefficient of the fibre will be measured soon in a climatic chamber and this will ultimately allow the calculation of the actual temperature variation.

Data show a strong asymmetry along the y axis; this may be partially explained by the different materials of the box, with its base made of aluminium, which transfers heat differently than Plexiglass. An additional contribution may come from strain experienced by the fibers in the upper levels, due to the different thermal expansion of Plexiglass and aluminium.

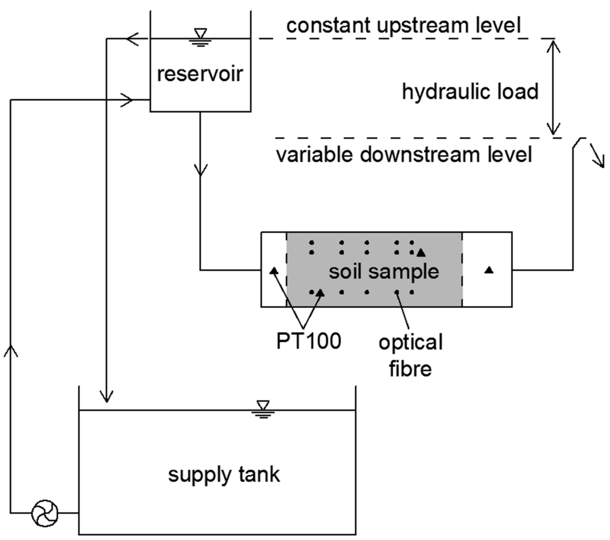

Figure 1. Setup of the experiment: a system made of two tanks and a pump supplies warm water at constant temperature and constant hydraulic head. The hydraulic load insisting on the sample is set by adjusting the height of exit point of the flow. Measuring system consists of 15 lines of optical fibre orthogonal to the flow direction, 4 resistive platinum sensors (PT-100) and 5 piezometers tubes inserted into one of the lateral walls of the box.

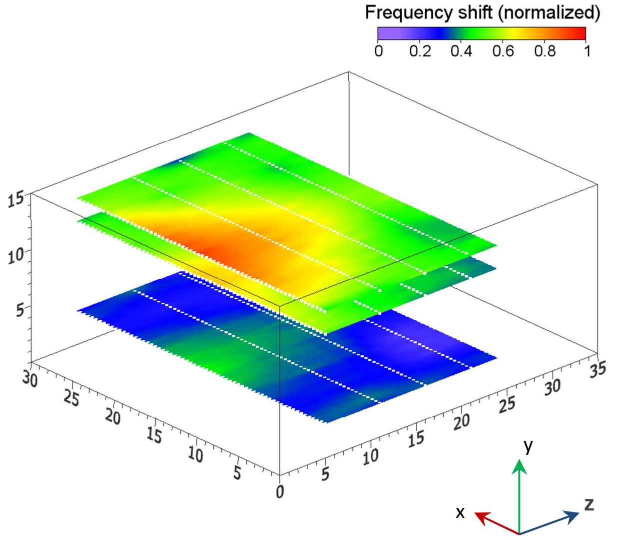

Figure 2. Normalized frequency shift measured by the fibre after 4 hours from the beginning of the test. Z axis coincides with the flow direction. The bounding box represents the overall extension of the sample and white markers indicate the position of the sensing fibre lines.

Ongoing investigations with a strain-free fibre deployment will provide better insight.

A slight asymmetry can also be observed in the x direction. The asymmetry is evident in figure 3, which shows the normalized frequency shift of the three sections of fibre closer to the water inlet (z = 5cm). A possible explanation for that is a non-uniform temperature of the water at the inlet. The fibre close to the bottom shows an interesting "W-shaped" pattern. This could be induced by a preferential water flow along the walls and/or buoyancy fluxes in the porous matrix, but further investigation is required to confirm such hypotheses.

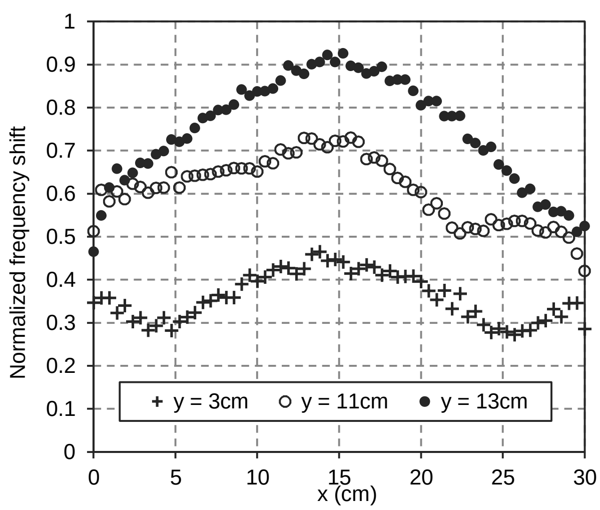

Figure 3. Normalized frequency shift measured after 4 hours by the fibres located at 5 cm from the inlet.

V. CONCLUSIONS

Preliminary data made clear the potentialities of the sensing platform. High density measurements highlighted details of the transfer of heat occurring in the sample, which wouldn't have been noticed even with numerous pointwise sensors. Further investigation is ongoing to determine the temperature coefficient of the fibre and reduce to minimum any strain experienced by the fibre during the tests.

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