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To cite this article: L Di Gennaro *et al* 2022 *Smart Mater. Struct.* **31** 065022

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An innovative geotechnical and structural monitoring system based on the use of NSHT

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Received 4 November 2021, revised 27 February 2022

Accepted for publication 22 March 2022

Published 18 May 2022



CrossMark

Abstract

The development of innovative early warning systems (EWS), structural health monitoring (SHM) and structural health monitoring and reinforcement (SHMR) systems is essential to prevent the occurrence of potentially dangerous events on engineering works, buildings and in the natural environment. Their effectiveness can be improved by using new generation sensors able to realize widespread, low-cost monitoring at increasing spatial and temporal resolution. The main aim of the research is, therefore, to develop a versatile strain transducer capable of monitoring elements of different nature such as slopes, buildings and linear infrastructures performing distributed real-time measurements. The paper introduces a new smart hybrid transducer (NSHT), a strain transducer belonging to the distributed optical fiber sensors family, appositely designed to overcome the drawbacks of traditional solutions. An experimental laboratory setup was arranged to test its reliability and a comparison between measurements retrieved by the NSHT and traditional devices were done. The results showed that the NSHT is able to perform strain monitoring with spatial resolution as high as 5 cm and accuracy comparable to that of the traditional devices. Finally, an integrated structural and geotechnical monitoring system architecture based on its use is proposed for the Petacciato site, where a deep-seated landslide affects the historical town and some infrastructures. To realize a single communication line in such a complex monitoring system, where multiple elements have to be monitored, a specific tool was also designed and tested, that allows the exact spatial identification of the various elements under observation. Although on-site validation is needed,

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these early results are encouraging and demonstrate that the NSHT is a low-cost transducer with great potential and that, looking forward, it can be used to increase the effectiveness of the existing EW, SHM and SHMR Systems. The development of systems involving NSHT also follows the new approach to innovation policy contributing to different points of the 2030 Agenda

Keywords: EWS, SHM, BOTDA sensing technique, monitoring, smart strain transducer

(Some figures may appear in colour only in the online journal)

1. Introduction

The climate changes and continuous land consumption make urbanized territories increasingly vulnerable and risks subjected to natural disasters. The exposed areas require a strong effort for their surveillance and protection to prevent the occurrence of potential adverse events.

The development of innovative and effective early warning systems (EWS), structural health monitoring (SHM), and structural health monitoring and reinforcement (SHMR) systems is crucial with this perspective. These systems should be able to quickly detect the potentially dangerous events that occur in a specific area or affect engineering works, in order to define an appropriate strategy with stabilization works or with structural reinforcements. They should contain traditional and innovative, distributed and punctual sensors and the collected information must be easily managed remotely by a system of components capable to acquire, processing and sending information and alerts. Several studies and analyses exist in the literature on the use of geotechnical EWS or SHM based on measurements performed by a network of punctual sensors like strain gauges, accelerometers, inclinometers, laser sensors, Doppler, reticles, and multi-core optical fibre [1–6]. However, these systems are not so effective for monitoring of deep-seated landslides and of infrastructures interacting with them (bridge, railway tracks, etc) as they can provide only local data, with the risk of missing critical points.

In the last decade, a new type of distributed strain sensors based on the use of optical fibres has been tested both for structures and geotechnical applications. That's because fibre optic sensors have a lightweight, small size, and high sensitivity performance; they are becoming even cheaper over the years [7, 8].

First attempts to use optical fibres in the geotechnical field were done to delimit the boundaries of a landslide body in a natural slope subjected to extremely slow movements [9], to monitor seepage and strain of embankment dams [10, 11] to analyse the behaviour of geosynthetics and reinforced earth [12, 13] and for early-detection of fast landslides [14–16].

Optical fibres have also been used for the measurement of soil displacement profiles based on the principle of the inclinometer tube [17, 18] instrumented an embankment slope with optical fibre sensors glued along an inclinometers tube showing that the array of sensors was able to detect the increase of soil strain during rainwater infiltration. However, the cost of such type of monitoring was not competitive and also technical

problems arising during the installation made this application only a prototype.

Moreover, technical literature both in structural [19–22] and in geotechnical fields [23, 24] involves monitoring systems based on fibre Bragg grating (FBG) sensing technique: with this technique, only small portions of the optical cable constitute the sensors. In this way, the main limitation of the traditional instruments, that provide local information not representative of the entire element to be monitored, is not overcome.

Further investigations highlighted that another shortcoming of the optical fibre sensors for landslide monitoring is the not still fully understood coupled interaction between the sensor and the soil [25–27]. Indeed, in most of the performed applications, the optical fibre sensor is simply embedded into the soil and, as the two materials in contact have different stiffness, the stress transfer between the soil and the sensor is not completely assured also depending on the overburden pressure. Heavy environmental conditions often damage the not-protected sensor, moreover.

Optical cables directly connected with structures or with inner iron reinforcement, in tunnels and single structural elements such as concrete pillars and beams, have been tested in order to realize smart structures that allow continuous monitoring [28–30]. In other studies, reinforcement interventions with smart composite bars are proposed [31–34]: the bars are equipped with optical cables so that the structural reinforcement elements represent the sensors themselves. Monitoring with smart bars, however, allows acquiring information about the reinforcement intervention itself rather than on the health of the overall structure.

In [35] two integrated systems with fibre optic wires and textiles are presented. The first, based on optical time domain reflectometry (OTDR) technique, is used for concrete crack detection: results show that there is no correlation between measurements and crack sizes and the breakage of the fibre can be used only as an indication of the status of the structural health. The second system is constituted by optical fibres embedded in a grid-like carbon composite able to perform multi-point sensing whose reliability has been evaluated through elongation tests. Results have shown that, in this latter case, the sensor can provide quantitative information. However, it remains a pointwise sensor.

A valid contribution to the SHM field is provided by the employment of distributed optic fibres sensors (DOFS) based on the Brillouin scattering technique. These sensors can

measure strain and temperature profiles along optical fibres overall, overcoming inherent pointwise sensors limitations. A smart fibre reinforces polymers (FRP) sensor was presented by [36] where strain and temperature sensing optical fibres have been inserted in the composite structural warp. The sensor was directly applied to the structure embedded in an epoxy matrix. Tests demonstrated the reliability of the sensor for crack detection. A similar sensor was tested by [37] with Brillouin optical time reflectometry detection technique for the realization of a long sensing circuit on an iron bridge. The project well represents the potentiality of DOFS despite some problems, such as the loss of signal in portions of the circuits.

In conclusion, the limits of the optical fibre sensors, used for strain measurements in both structural and geotechnical applications, can be summarized as follows:

- the connection system between the sensor and the element under observation does not realize a fully coupled stress transfer making difficult the interpretation of the monitoring;
- the use of glue to fix the fibre on the structural element does not assure the possibility to perform long-time observation as it is unstable from a thermomechanical point of view and disconnections of the fibre in many points along the element can occur which vanish the efficiency of the system;
- the sensor needs an appropriate coating when used in hard environments, such as slopes and rail-tracks, to avoid its damage;
- monitoring over long distances (in the order of several tens of meters) requires appropriate technical solutions for transport and assembling the distributed strain transducer.

The new smart hybrid transducer (NSHT) [38, 39] represents the overcoming of all the limits highlighted above. It can be used for landslide monitoring, as a smart inclinometer, along linear infrastructures, as an SHM tool, or to pursue the dual scope of reinforcement and monitoring of structures by realizing an SHMR system, providing distributed measurements.

In the paper, we show the experimental laboratory tests carried out to endorse the accuracy and reliability of the NSHT transducer, highlighting the advantages, limits, and future perspectives for its in-field use.

The paper aims, in conclusion, to present the application of NSHT in an actual case where both structural and geotechnical monitoring is required. A proposal of the architecture of an integrated structural and geotechnical early warning system (ISG-EWS) based on its use is presented. It is related to the case history of the deep-seated Petacciato Landslide (Adriatic coast, Italy) that affects both lands and railway and highway infrastructures.

The ISG-EWS can be considered as an action to ‘generate an unstoppable movement pushing for the required transformations’ in the 2030 Agenda for Sustainable Development, which set out a 15 year plan to achieve the Sustainable Development Goals, with particular reference to SDG#11 (Sustainable cities and communities), SDG# 9 (Industry, innovation

and infrastructure; building resilient infrastructure), that reaffirm the interrelationship between Disaster Risk Reduction and SDGs, and SDG#17 (Partnerships for the goals; finance).

2. Materials and methods

2.1. NSHT: new smart hybrid transducer

The NSHT is a strain transducer that belongs to the DOFS type sensors family based on detection by an optical fibre wire, capable of working over great distances. In the NSHT the sensor consists of a tight-buffer standard single-mode fibre queried with the traditional Brillouin optical time domain analysis (BOTDA) sensing technique. The transducer is composed of several elements with different functions. The optical fibre is embedded in a resin matrix between two composite material tapes. The fibre cable runs with a U-shaped path to determine an In and an Out segment, whose endpoints are connected to the control unit (figure 1). The external tapes prevent damage of the sensor in hard environments; give a flexible structure to the transducer for easy application on bend-shape elements and wrapping around support during transport; realize a fully coupled stress transfer between the sensor and the monitored element. The transducer can be manufactured with a length of up to tens of meters. To ensure the correct positioning and the perfect adhesion of NSHT on the support, the transducer is provided with fastening elements every 50 cm (figure 1), moreover.

2.2. BOTDA: Brillouin optical time domain analysis

The operative principle at the basis of the sensing technique is the Stimulated Brillouin Scattering phenomena induced along the optical fibre. It allows performing distributed measurements of strain and temperature over large distances and with high spatial resolution.

The basic idea underlying the use of this sensing technique can be understood from the Brillouin frequency shift (BFS) relationship:

$$v_B = 2 \frac{nV_a}{\lambda_0} \quad (1)$$

where n is the effective refractive index of the fibre, V_a is the acoustic velocity, and λ_0 is the optical wavelength. As the effective refractive index and the acoustic velocity vary with temperature and strain, the BFS changes in response to local environmental variations. The BFS has a linear dependence on temperature and strain over a wide range, and it can be written as:

$$\Delta v_B(T, \varepsilon) = C_\varepsilon \Delta \varepsilon + C_T \Delta T \quad (2)$$

where C_ε is the strain coefficient and C_T is the temperature coefficient. These coefficients are mostly determined by fibre composition, pump wavelength, fibre coatings, and jackets. Typical values are $C_T \approx 1 \text{ MHz } ^\circ\text{C}^{-1}$ and $C_\varepsilon \approx 500 \text{ MHz } \%^{-1}$ [40].

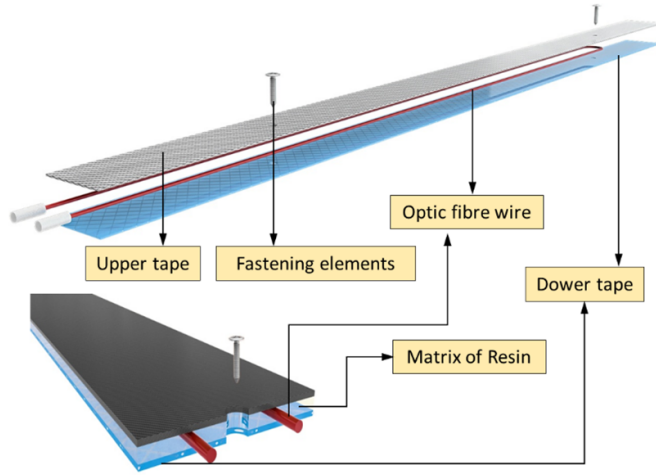


Figure 1. Sketch of the NSHT transducer.

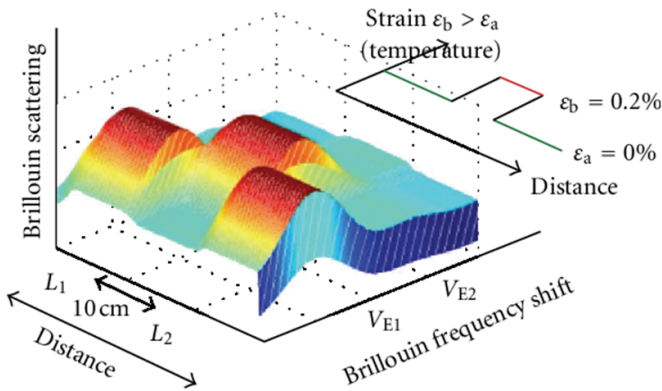


Figure 2. BOTDA principle [41] (CC-BY 3.0).

In the BOTDA, the BFS profile along the fibre is retrieved by recording the interaction between a pulsed pump electromagnetic wave and a counter-propagating stationary wave (the probe wave) as a function of time. Any deviation of the local BFS from a reference measurement is an indication of a change of strain and/or temperature that occurred at that location along the optical cable (figure 2). BOTDA sensors allow measuring strain and temperature profiles up to tens of kilometres with a typical strain accuracy of $20 \mu\epsilon$, a temperature accuracy of 1°C , and a spatial resolution of decimeters.

In the following tests has been employed a BOTDA control unit which setup is shown in figure 3. A distributed feedback laser diode (DFB-LD) operating at $1.55 \mu\text{m}$ wavelength provides the pump and probe signals. The electro-optic intensity modulator IM1, driven by an RF synthesizer and operated in the suppressed carrier regime, is employed to generate two sidebands around the laser frequency [40].

The FBG selects the lower sideband (Stokes component) for the probe beam. The modulator IM2, driven by an electrical pulse generator, generates the pump pulse. Two erbium-doped fibre amplifiers (EDFA1 and EDFA2) are used to amplify the probe and pump beams before they enter the sensing fibre. A polarization scrambler is employed to average out the polarization-related Brillouin gain fluctuations. Finally,

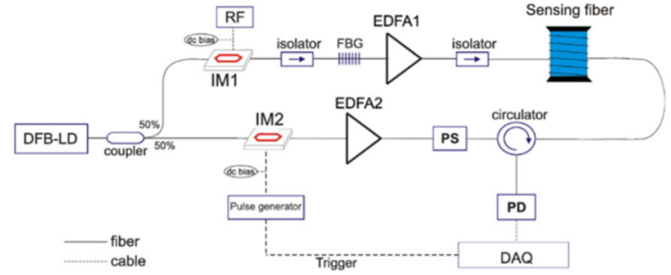


Figure 3. Experimental BOTDA setup. DFB-LD: distributed feedback laser diode; IM: intensity modulator; RF: radiofrequency generator; FBG: fibre Bragg grating; EDFA: erbium-doped fibre amplifier; PS: polarization scrambler; PD: photodiode.

the Stokes beam emerging from the sensing fibre is detected by a 1 GHz bandwidth InGaAs photodiode, whose output is sampled at 2 GS s^{-1} by a 1 GHz bandwidth acquisition card Data Acquisition Unit (DAQ).

3. Laboratory tests

To test the reliability, accuracy, and potential in-field use of NSHT, different laboratory tests were performed.

The experimental campaign can be divided into two phases. The first one was performed to verify the accuracy of the measurements (calibration tests), the second one focused on the analysis and overcoming of any operational problems, assuming possible field applications.

In each test, performed under constant temperature, the data was collected and processed using the BOTDA control unit shown in figure 3 and the data was processed with Matlab software.

3.1. Calibration tests set up

In this phase, three prototypes were made by combining different types of composite tapes and using two different types of optical fibre. In detail, glass and/or carbon fibre tapes were used as coating and both the bending and the non-bending sensitive fibre type were tested as sensing elements. Details of test setups are reported in table 1. In the following text, it will be used the acronym GG for prototypes realized with two glass tapes and the acronym CG for that realized with a carbon tape and a glass one.

A first test was carried out to simulate a geotechnical application by realizing a smart inclinometer instrumented with two prototypes (test n. 1 in table 1). The second test was performed on a beam-like element instrumented with a single NSHT prototype (test n. 2 in table 1).

In both experiments, NSHT was installed along an aluminium tube consisting of several segments linked together by collars (standard inclinometric tube) (figure 4).

The reliability of the NSHT was tested by performing, in the same tubes, standard vertical and horizontal inclinometric measurements (RTS Instruments and Sol-Experts Ltd) to realize a benchmark.

Table 1. Test set up.

Test	Type	Fibres tape	Transducer length (m)	Optical fibre	Control unit resolution (cm)	Inclinometric resolution (cm)
n. 1	GG	Glass–Glass	4.0	Non Bending Sensitive	40	50
n. 1	CG	Carbon–Glass	5.25	Bending Sensitive	40	50
n. 2	GG	Glass–Glass	6.50	Non Bending Sensitive	5	25

**Figure 4.** Sketch of two segments joined with collar; 1-radius = 80 mm; 2-radius = 86 mm.

The first test was carried out in outdoor environment and it was realised to simulate a vertical smart inclinometer: an aluminium tube 7.6 m long was equipped with a GG transducer 4.0 m long and a CG transducer 5.25 m long. The two transducers were installed along the tube with a 90° rotation (figures 5(a) and (b)). The tube was disposed vertically along a wall and fixed to it using flexible straps. Then, to obtain a deformed configuration, it has been subjected to prescribed displacements inserting four spacers between the tube case and the support in correspondence of the straps (figures 5(c) and (d)).

The second test was carried out in indoor environment on a horizontal pipe 7.5 m long, equipped with a 6.25 m GG transducer along its intrados. The tube was secured at one end and supported on the other one where a vertical displacement of 14 cm was applied by inserting spacers (figure 6). The aluminium pipe, in this second test, had the first collar at 2.85–3.15 m from the fixed end, a second one at 5.85–6.15 m, 5.85–6.15 m.

3.2. Results

Considering that traditional inclinometers provide displacement profiles, whereas the NSHT provides strain profiles, the first ones have been derived to obtain comparable data. In the case of the vertical inclinometer (Test n. 1), inclinometric data have been firstly transposed to the positions occupied by the NSHTs. This, because the displacement profiles refer to the axis corresponding to the rails of the pipe AA' and BB' while prototypes GG and CG lie on different axis aa' and bb' rotate of 45° with respect to the first ones (figure 5(b)).

Figure 7 shows displacement diagrams along the axis a–a' and b–b' (figures 7(a)–(d)), the rotation diagrams (first derivative figures 7(b)–(e)) and the comparison between NSHT and vertical inclinometric strain diagrams (second derivative figures 7(c)–(f)). The strain profiles are comparable for trends and values.

Strain values referred to CG installed along the a–a' axis, differ in an average of about $4.30 \times 10^{-5} \mu\epsilon$ from the inclinometer ones falling within the field of instrumental error of the inclinometer. The maximum and the minimum of the functions are positioned approximately at the same depth, moreover: the minimum in the interval 4.25–4.40 m and the maximum in the 1.75–2.00 m one, revealing the accuracy of the new transducer.

Data retrieved by GG prototype positioned along b–b' axis (figure 7(c)) present higher scatter when compared to those retrieved by the CG one (figure 7(f)). In detail, the greatest deviation between the inclinometer and the GG data is $1.16 \times 10^{-4} \mu\epsilon$, and occurs between 2.00 and 3.00 m from the inclinometer casing top, at a position close to the collar joining two segments of the tube. It has to be highlighted that also in this case the maximum and the minimum of the functions are positioned approximately at the same depth: the minimum in the interval 2.40–2.80 m and the maximum in the 4.75–4.80 m one. The higher differences referred to the strain values of the GG prototype are probably due to the different used sensing cables. The 'bending sensing' fibre type, indeed used for the GG prototype, suffers a more significant loss of signal in presence of relatively high curvatures and this, in turn, reflects on a higher noise of the signal. Instead, the non-bending sensitive fibre presents a lower loss of signal, and it is better suited to the purpose. It cannot be also excluded that the GG manufacturing process suffered some little, but not negligible, localized curvatures of the fibre which affected the accuracy of the measurements.

The results of the second test, performed to simulate a beam element, are reported in figure 8.

As for the first test, the first two diagrams (figures 8(a) and (b)) illustrate respectively the displacement function and its first derivative obtained by the post elaboration of the horizontal inclinometer raw data. From the analysis of the rotation diagram, it can be seen that two main inflexion points are present at about 1.75 m and 4.75 m of the tube length. In the related strain diagram, these relevant points represent the two minimum of the function where the measured strains, in their absolute value, are maximized.

The NSHT trend and values do not differ significantly from the ones derived by the standard inclinometer setup (figure 8(c)).

Strain values referred to NSHT differ in an average of about $4.34 \times 10^{-5} \mu\epsilon$ from the inclinometer ones falling as in the previous test within the field of instrumental error of the inclinometer. The maximums and the minimums of the functions are positioned approximately at the same depth, moreover: the first negative peak 1.70–2.00 m, the second negative peak in the interval 4.25–5.50 m, and the maximum in the

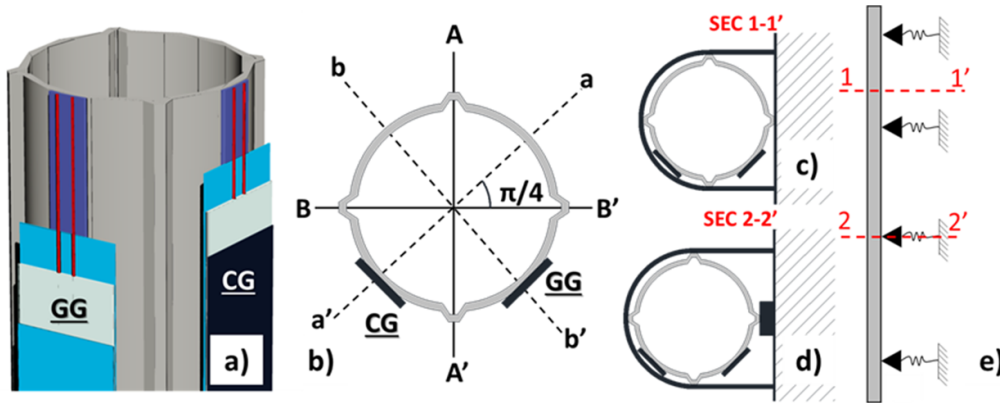


Figure 5. First test setup: (a) sketch of the specimen; (b) prototype plan view; (c) section 1-1'; (d) section 2-2'; (e) static scheme.

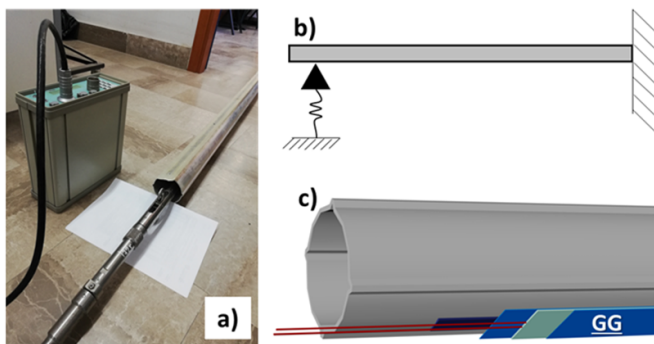


Figure 6. Second test set up: (a) instruments; (b) static scheme; (c) sketch of the specimen.

7.00–7.50 m one. Also in this test, probably the use of the prototype realized with the ‘bending-sensitive’ fibre and related manufacturing problems may have influenced the results.

The experimentation carried out gave positive results in terms of reliability and accuracy of the data obtained by the innovative sensor. The difference between the strain values of inclinometers and NSHT prototypes is on average 7.50×10^{-5} fully falling within the field of instrumental error of the inclinometer.

Furthermore, it revealed that the use of bending-sensitive fibres is not suitable for in-field use as a loss of signal was found in some localized areas with consequent worsening of measurement accuracy.

3.3. Start point identifier (SPI)

In each performed test, the acquisition control unit contains an abundance of fibre optic wire which, at the time of measurement, is detected and provides data. Also, the junction cables between the control unit and the transducer are sensing elements and provide data. This means that there is a multitude of data related to the entire length of the optical fibre circuit, not only to the transducers (control unit + junction + NSHT). Thus, it is very difficult to detect where data refer to the NSHT,

or to other elements, except through time-consuming data processing. Also in field applications, where NSHT hundred of meters long could be used to monitor different engineering works, the need to identify unambiguously the single part of the circuit is crucial.

Indeed, to avoid a false alarm every change of BFS must be correctly positioned allowing the right addressing of the signal to the elements under monitoring.

To this aim a tool called start point identifier (SPI) has been appositely developed. It is based on the idea that, thanks to the dependence of the BFS on temperature (equation (2)), applying a significant temperature variation in a localized point along the NSHT, the corresponding increase of the BFS can be easily readen in the BFS diagram.

SPI is a removable external device of small dimensions fitted with a heating cartridge and a controller for setting the temperature (figure 9).

Directly applying this device on the transducer, the thermal gradient is transferred to the optic fibre within the NSHT.

To test the effectiveness of the SPI, the device has been positioned on a prototype of NSHT 9 m long connected to the acquisition unit by two patch cables.

The performed test consisted in applying different thermal gradients, positioning the SPI in the initial part of the NSHT (figure 9(b)). Different measurements have been carried out setting the SPI at the following temperatures:

- Zero Reading $T_0 = 22^\circ$ (ambient temperature)
- $T_1 = \text{SPI at } 70^\circ$
- $T_2 = \text{SPI at } 60^\circ$
- $T_3 = \text{SPI at } 40^\circ$

Figure 10 illustrates the changes of the BFS along the transducer that occurred during the applied increases of temperature. The graphs show that the thermal gradients applied on the NSHT reached the optic cables returning the presence of the frequency peaks in correspondence of the section in which the SPI was positioned.

In conclusion, the detection of the peaks of frequency demonstrates that the presence of SPI on the NSHT ensures an

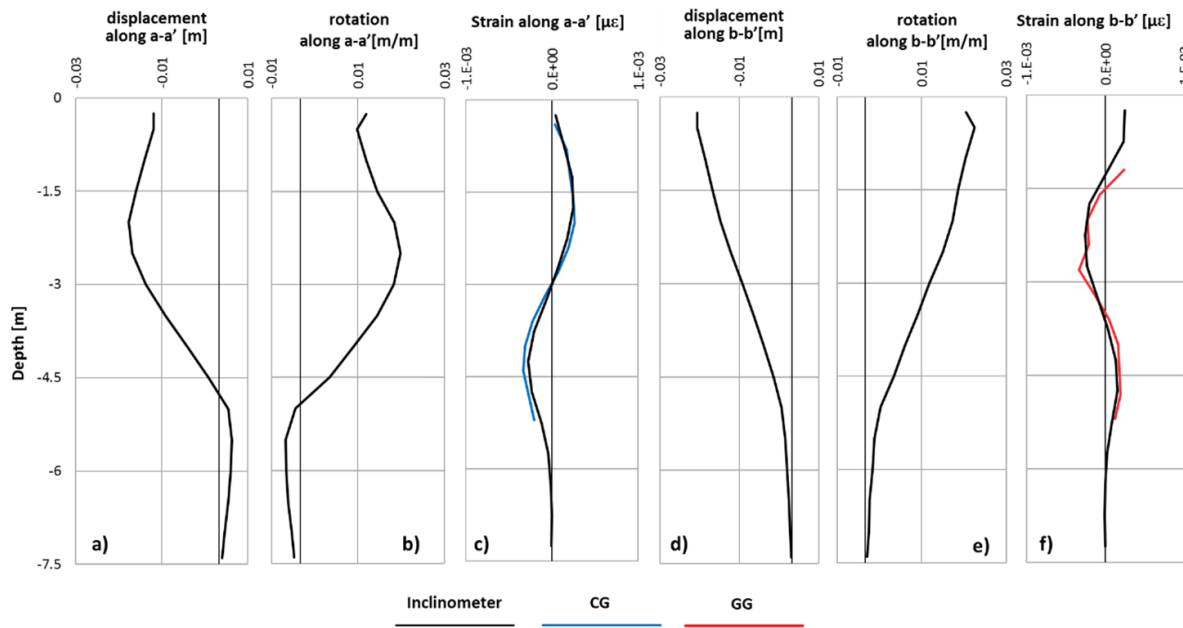


Figure 7. First test result: (a) displacement diagram along a-a' axis; (b) rotation diagram along a-a' axis; (c) strain diagram along a-a' axis; (d) displacement diagram along b-b' axis; (e) rotation diagram along b-b' axis (f) strain diagram along b-b' axis.

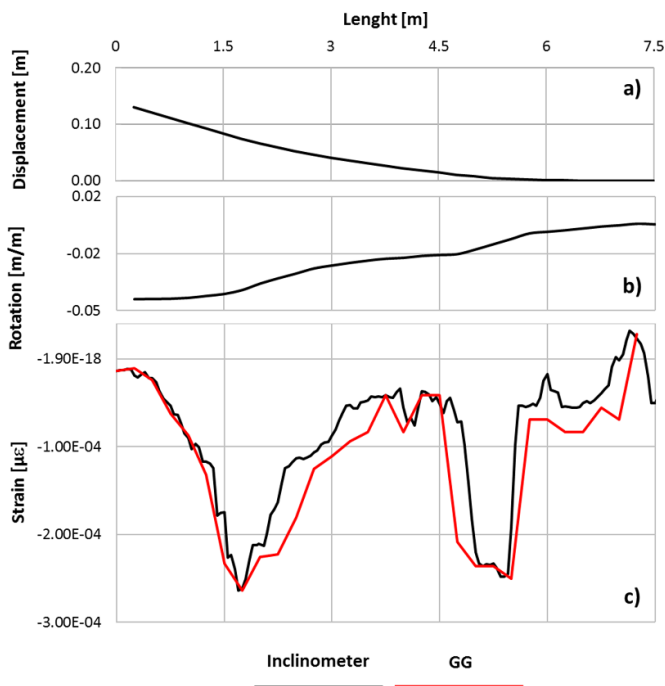


Figure 8. Second test results (a) displacement diagram; (b) rotation diagram (c) strain diagram.

easier interpretation of the data especially if applied in complex sensing circuits.

4. Possible applications of the NSHT in integrated structural and geotechnical monitoring systems

As it was designed, NSHT can be easily used in combined Structural and Geotechnical EWSs.

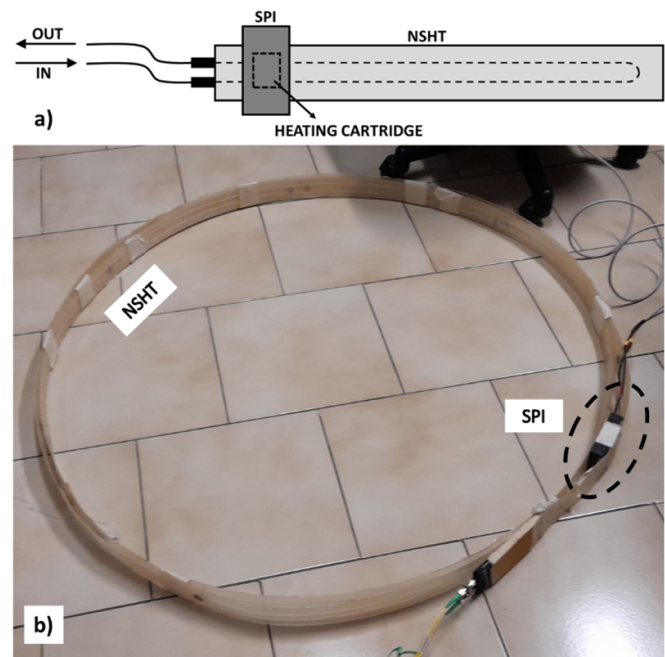


Figure 9. SPI test: (a) setup scheme; (b) picture of the test.

Several applications in structural fields can be supposed. The transducer could be used for the realization of smart reinforcement interventions where the transducer plays at the same time the role of reinforcement and monitoring (SHMR).

It will be able to provide relevant information about the intervention effectiveness as well as the health of the structure overall.

NSHT monitoring the deformation state of the construction elements can be installed in buildings (concrete, wood,

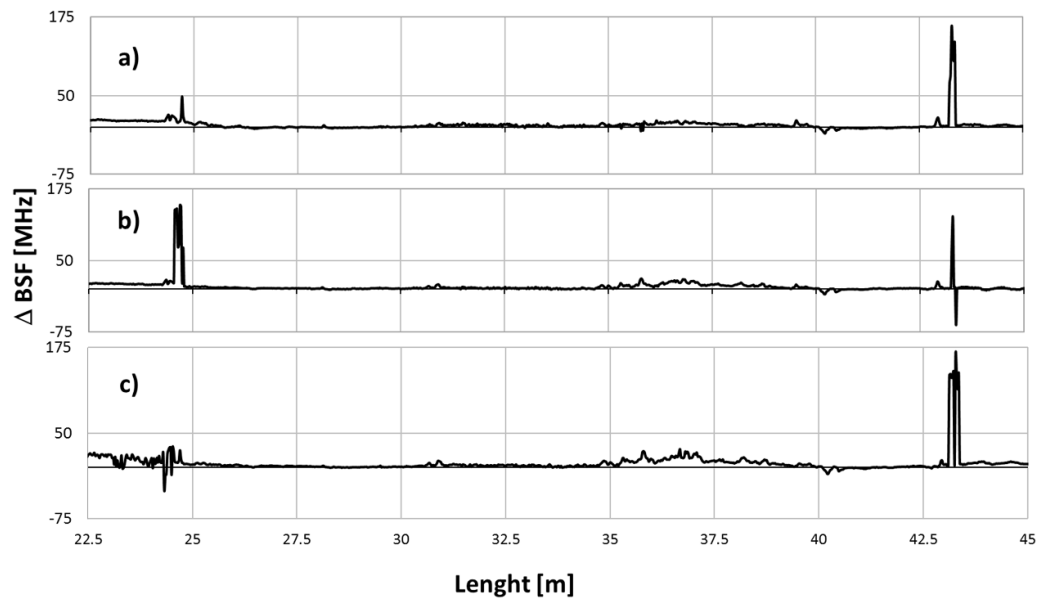


Figure 10. Changes of BSF after application of: (a) T_1 ; (b) T_2 ; (c) T_3 .

steel and masonry structures), in civil infrastructures and for cultural heritage monitoring.

The NSHT can be used for landslide detection by realizing and installing in site smart vertical inclinometer, as the one illustrated in figure 5. In the case of activation or reactivation of a landslide, the soil undergoes continuous deformations, especially localized around the sliding surface in the so-called shear band. The device, which is able to monitor in real-time the trend of the vertical soil strain profile, will give rise to information about the rate of movement and the depth of formation of the sliding surface.

In the case of geotechnical application as Smart Inclinometer, it can be used alone, casehardened in a borehole, or installed in the same hole along a standard inclinometer tube. In this latter case, the presence of two transducers operating in parallel, a traditional inclinometer and the NSTH, should eliminate the risk of false alarms. In presence of an alert signal, thanks to the redundancy of the system, NSHT measurement can be validated with the traditional one.

The simultaneous use of traditional sensors, such as strain gauges, installed in parallel with NSHT could furnish a higher safety degree to the monitoring system.

4.1. Case study: the deep-seated landslide of Petacciato

Starting from the case study of the Petacciato landslide, a deep-seated slope movement close to the Adriatic coastline in Italy, the research group with the collaboration of Molise Region has developed an EWS system architecture that integrates the already working traditional monitoring system with the innovative NSHT transducers.

The case study fits particularly with the aim of the research because the complex phenomenon involves structures, infrastructures, the town of Petacciato, its cultural heritage, and the slope. Several studies [42–44] have been

carried out highlighting the complexity of the landslide kinematics.

As shown in figure 11, the landslide deeply affected strategic infrastructures, such as the Adriatic railway line and the A14 motorway route, as well as other secondary roads, classified as infrastructures at high risk.

The relocation of the civil engineering works is not possible due to the great areal and in-depth extension of the slow-moving soil mass. So there is the need to allow the coexistence of interactions between them and the slope movements by the implementation of an effective geotechnical and structural EWS.

The landslide has been widely investigated and monitored since 1981 by various institutions and authorities by means of a number of mainly pointwise sensors (about 70 inclinometers and 50 infrastructures devices) as schematically illustrated in figure 11.

After reactivation of movements in 2015, the operating EWS was integrated with several automatic inclinometric fixed probes positioned at selected depths in order to have in-time continuous slope monitoring. Although the interaction of the two soil displacement detection systems (the conventional inclinometers and the fixed probes), increased the level of efficiency of monitoring, it was not always able to detect the formation of new shear bands and to reveal the associated soil movements in time.

The integration of the system with distributed automatic sensors is crucial to avoid missing the individuation of critical points. This is the reason because the integration of the already operating EWS with the NSHT could work. The main reasons can be summarized as follow:

- the transducer, used as a smart inclinometer, with its spatial resolution higher than 20 cm realizes, de facto distributed measurements avoiding the risk of missing the individuation of sliding surfaces of new formation;

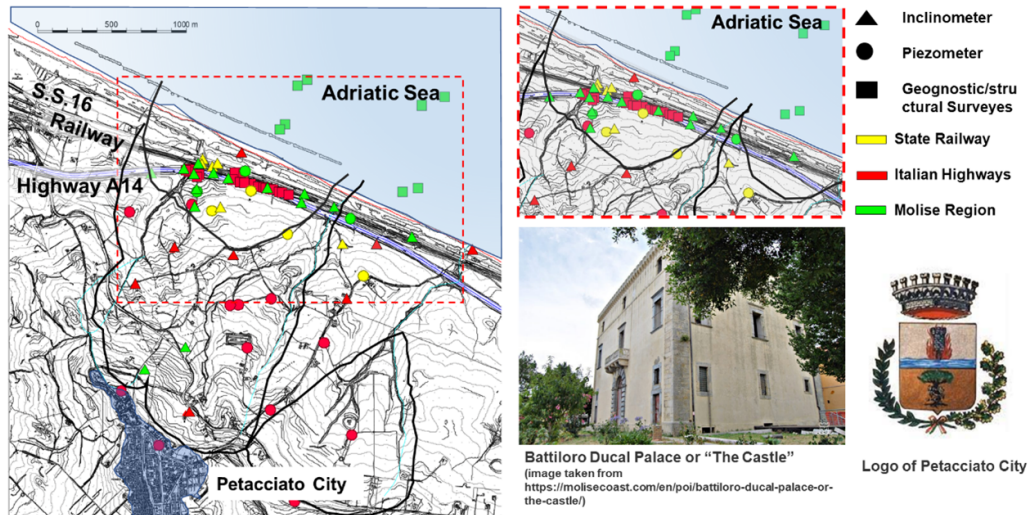


Figure 11. Morphological map of the complex landslide system, location of the instrument, picture of 'the castle' of Petacciato in the homonymous city, the logo of the city.

- it can reach a length greater than 100 m, individuating the deepest sliding surfaces and performing continuous in-time stand-alone measurements;
- the transducer, when installed along an inclinometer casing tube, allows checking the measurements with those realized by a traditional inclinometer increasing the reliability of the system;
- the transducer can be also used for monitoring the strain state of the exposed structures; the cheapness of the sensor allows investigating wide areas of structures.

In the following, the design of an integrated structural and geotechnical monitoring system (ISGMS), though to be applied to the case of the Petacciato landslide, will be proposed.

4.2. System architecture

The proposed system architecture includes the installation of various peripheral NSHT transducers, for both slope and infrastructures monitoring, directly connected to a centralized data acquisition and transmission (CDAT) system.

The key aspects of the system are:

- The strain state of the highway viaduct will be provided by deformation measurements performed by means of NSHT transducers located along the decks, the edges of the roadway and the entire length of the viaduct;
- The railway monitoring will be performed by the direct installation of NSHT along the tracks;
- The monitoring of the highway pavement deformation will be provided by strain and temperature measurements detected with the NSHT directly inserted inside the pavement;
- The soil displacement monitoring will be provided by measurements performed with NSHT transducers used as smart vertical inclinometers with a length exceeding 100 m.

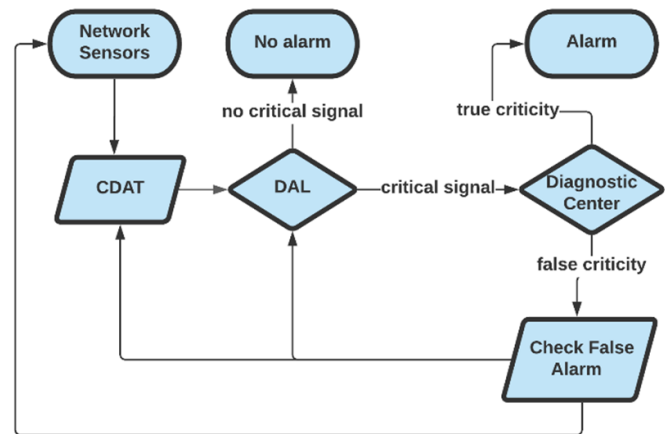


Figure 12. System architecture flowchart.

The monitoring system gives rise to a single communication and sensing line that involves structures, infrastructures and soil. This configuration allows querying the entire network of NSHT from a single access point, corresponding to the CDAT unit (CDAT).

CDAT sends data to the data acquisition local unit that detects the occurrence of a critical signal exceeding the pre-set threshold value. The information is sent to a diagnostic centre that provides a deeper analysis including querying traditional sensors. In case the critical signal is true, an alarm will be sent.

If the diagnostic phase verifies that the signal detected is incorrect, the system provides a check phase: all the parts of the system must be checked to understand the causes of malfunction.

A schematic representation of the system architecture is reported in figure 12.

The system needs management, diagnosis and coordination software that provides the sampling frequency of the data transmission period, for each sensor, as well as the alert and alarm thresholds.

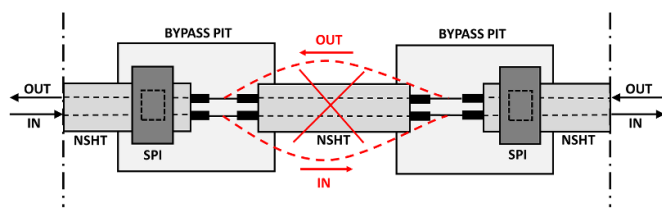


Figure 13. Bypass scheme.

It has to be highlighted that it allows performing continuous monitoring of the complex NSHT network using a single sensing line. The presence of SPI installed in crucial points allows distinguishing the different parts of the sensing line, easily identifying the position of those not subject to strain. In case of breakage of one of the transducers, to isolate and, eventually, replace the broken sensor, it will be possible to operate a bypass as shown in figure 13.

5. Economic aspects: the ISGMS as de-risking infrastructure

In a context of limited public fiscal space and private saving glut, our ISGMS architecture, based on NSHT, can be very appreciated as a new de-risking infrastructure to make economies ‘investable’ by global finance in the current times of a market-based finance logic. The development of this infrastructure can be seen as a very important action performed in order to contribute to the implementation of the SDGs of the 2030 Agenda, with particular reference to SDG#11 (Sustainable cities and communities), SDG# 9 (Industry, innovation and infrastructure; building resilient infrastructure), that reaffirm the interrelationship between Disaster Risk Reduction and SDGs, and SDG#17 (Partnerships for the goals; finance).

6. Conclusions

In Italy, as well as in many countries in the world, many structures and infrastructures suffer threats being located in areas where slow-moving landslides are periodically reactivated.

In this paper, a new type of distributed strain transducer NSHT based on BOTDA sensing technique for implementation in advanced geotechnical and structural monitoring systems has been proposed. To assess the accuracy and the reliability of the NSHT, laboratory tests have been carried out and their results have been shown. In each test, a traditional sensor has been used too. The comparison between traditional and innovative measurements has demonstrated the effectiveness of the NSHT as a strain transducer of high spatial resolution.

Another main advantage of this type of sensor is that it can be used for both landslides monitoring, as smart inclinometer, and infrastructural monitoring, as SHM system, overcoming the limits of traditional solutions based on pointwise strain measurements.

To avoid false alarm detection due to the incorrect positioning of the signal along the sensing line, a prototype called SPI has been appositely designed and tested.

Finally, starting from a complex case of the deep-seated landslide of Petacciato, an architecture of the NSHT monitoring system has been presented. It has been thought to improve the efficiency of traditional EWS concerning a case study located in Southern Italy where due to big areal and depth extension of the slope movements the adoption of effective EWS is the only feasible strategy for landslide risk mitigation.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors gratefully acknowledge the IREA-CNR of Naples for its helpful support.

Funding

This research was funded by the Università degli Studi della Campania ‘L. Vanvitelli’, grant Programma VALERE: ‘VANviteLli pEr la RicErca’, DDG n. 516-24/05/2018.

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