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Earth structures with integrated distributed sensors for multi-parameter measurements

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ABSTRACT: Distributed Fibre Optic Sensing (DFOS) is increasingly used in civil and geotechnical engineering to monitor the performance of structures during both construction and operation. Its primary advantage lies in the ability to continuously measure selected physical parameters along the entire length of the sensor, ranging from a few millimetres to several hundred kilometres. This makes DFOS especially valuable for monitoring linear infrastructure such as tunnels, roads, highways, bridges, pipelines, dams, and embankments. This article outlines the fundamental principles of DFOS, highlighting its key benefits and limitations, and explores its practical applications in several road embankments, including one of the tallest in Poland. Depending on the specific requirements of the project, the type of DFOS sensor and system configuration, measurements can provide detailed information on distributed strains, displacements (settlements), and temperatures. The article also presents best practices and insights into practical considerations such as sensor and optical device selection, installation methods, thermal compensation, post-processing techniques, and data visualisation, to support the engineering interpretation of the results.

KEYWORDS: distributed fibre optic sensing (DFOS), geotechnics, strain, displacement, temperature, vibration

1 INTRODUCTION

Distributed fibre optic sensing (DFOS) enables the continuous measurement of selected physical quantities along the entire length of the linear sensor, extending even to hundreds of kilometres. This characteristic represents the principal feature of the technology and, simultaneously, its key advantage over conventional spot-based measurement techniques. The enhanced insight into structural performance — including the ability to identify localised events such as cracks, leakages and stress concentrations, as well as the weakest cross-sections — is continually broadening the range of practical applications in civil engineering (Bado & Casas, 2021) and geotechnics (Shi et al. 2021, Wang et al. 2024).

Despite the obvious benefits described above, the implementation of a successful DFOS-based system always requires an individual design tailored to the specific requirements and conditions of the given project. The analysis should encompass the selection of appropriate sensors and their physical–mechanical parameters, data loggers (optical interrogators) and their measurement characteristics, thermal compensation strategies (Bednarski et al. 2024), relevant installation procedures, and, finally, the methods of data post-processing, visualisation and interpretation. Although this design process is often challenging and demands expert knowledge, it is worth undertaking with care to ensure reliable data acquisition and long-term structural monitoring. This article briefly summarises the fundamentals of DFOS technology and presents practical applications in geotechnics, highlighting good practices in the field.

2 DISTRIBUTED FIBRE OPTIC SENSING

2.1 *Operation rules and basic parameters*

Continuous scanning of optical fibre to extract distributed values of various physical quantities is enabled by different light-scattering effects, including Rayleigh (Palmieri et al., 2022), Brillouin (Bastianini et al., 2019) and Raman (Li & Zhang, 2022) scattering. The first two are primarily used for measuring mechanical parameters, such as strain or vibration, whereas Raman scattering is used for temperature measurement. The sensors are physically connected to the interrogator and, based on its predefined settings, are virtually divided into smaller gauges arranged in series along the fibre length. The base length of each gauge determines the spatial resolution of the system (i.e., the number of sensing points per unit length of the sensor; see Fig. 1). When selecting an interrogator, the user must also consider factors such as accuracy, repeatability, measurand resolution, operating temperature range, acquisition time and measurement frequency.

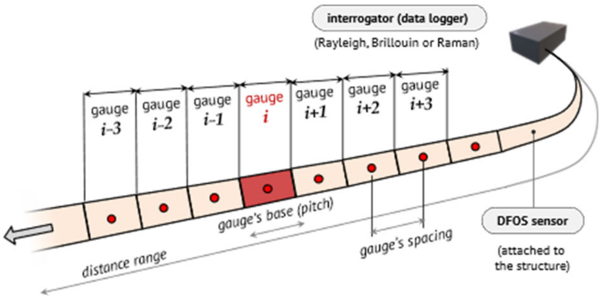

Figure 1. The basic configuration of DFOS system consisting of optical sensor and interrogator.

2.2 *Physical quantities*

In general, depending on the type of sensor and the choice of interrogator, four main quantities can be measured along the entire sensing path, as summarised in Fig. 2:

- Distributed Strain Sensing (**DSS**) – enables the detection and analysis of local events, including cracks (Howiacki et al., 2023), leakages, sinkholes, shear planes and stress concentrations.
- Distributed Temperature Sensing (**DTS**) – often used for strain-compensation algorithms or as an

independent technique for temperature-related events and, increasingly, in geothermal applications.

- Distributed Displacement Sensing (**DDS**) – requires a special type of sensor comprising at least two fibres appropriately arranged within the sensor cross-section (Bednarski et al., 2021).
- Distributed Acoustic Sensing (**DAS**) – allows measurements over very long distances (even exceeding 100 km) at extremely high frequencies (e.g., 50 kHz), making it an ideal solution for detecting various vibration sources (Zhu et al., 2022).

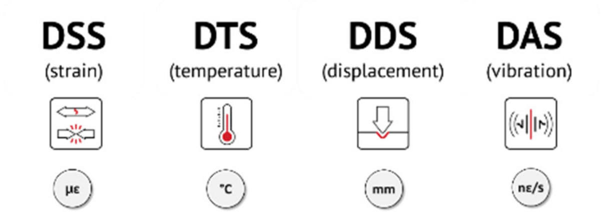

Figure 2. Physical quantities measured with DFOS approach.

Interestingly, and importantly for many applications, the aforementioned physical quantities can be measured using the same sensor, provided it is equipped with at least two independent optical fibres. In such cases, installation efforts are required only once, while the system's functionality can be easily extended at any stage of its operation (Piątek et al. 2023). This advantage also applies to future, yet unknown, developments in measurement apparatus, as DFOS sensors are based on standard fibres widely used in telecommunications, ensuring their long-term compatibility.

2.3 *Requirements for the sensors*

In contrast to telecommunication applications, sensors installed in geotechnical structures to measure safety-critical parameters must possess a carefully designed set of features. These include material properties, cross-sectional shape and size, internal and external design (e.g., monolithic single-material core with an external braid), tensile strength, elastic modulus, minimum bending radius, operating temperature range, and more. The properties of the sensor should always be analysed individually, taking into account the specific installation and operational conditions. Nevertheless, a set of fundamental general requirements that geotechnical sensors should meet is outlined below:

- High accuracy – ensured by direct transfer of the measured strain to the fibre, achieved through a monolithic cross-section (Bednarski et al. 2022) without intermediate layers that could cause slippage or debonding.
- Wide elastic range – enabling measurements under large deformations without yielding or damage, ensuring long-term reliability.
- Textured outer surface – providing adequate bond with the surrounding material to correctly reflect structural behaviour (e.g., braided or ribbed finish for embedded strain sensors).
- Resistance to harsh conditions – protection against mechanical and environmental impacts during transport, installation and service life.
- Durability and corrosion resistance – achieved through appropriate core materials.
- No pre-tensioning required – the sensor must work in both tension and compression zones without the need for field pre-tensioning.
- Modular delivery – sensors available in coiled sections, allowing easy connection of segments on site.
- Proven performance – validated in multiple geotechnical applications.

2.4 *Geotechnical installation insights*

All sensors should be installed in accordance with the previously developed design. In typical earth embankments, sensors are placed at selected layers in both longitudinal and transverse directions (see Fig. 3). During installation, care must be taken to maintain the minimum bending radius specified in the sensor's datasheet and to minimise excessive waviness or twisting of the sensors by providing appropriate stabilisation, for example using sand bedding or dedicated mounting elements.

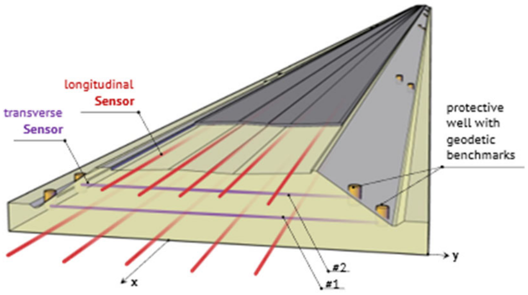

Figure 3. Typical installation of DFOS sensors in earth embankment.

Distributed fibre optic sensors operate primarily in the longitudinal direction, yet they remain sensitive to local actions acting perpendicularly to the sensor axis. Special care must therefore be taken to avoid, for example, contact with sharp aggregate grains. The safest approach is to use a narrow excavation lined with geotextile and filled with compacted sand, ensuring that larger stones cannot come into contact with the sensor (Figure 4).

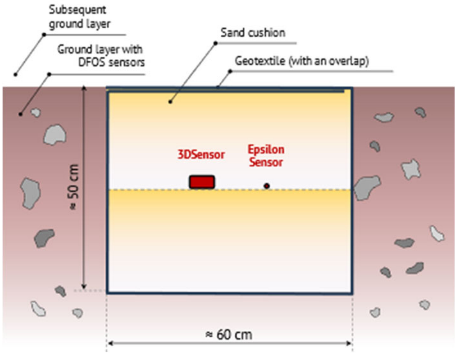

Figure 4. Recommended installation of strain and displacement sensors in sand cushion within the earth structure.

Where ground conditions allow and safety is ensured, sensors may be installed in a narrow trench, similar to the method used for telecommunications cables, rather than in a relatively wide excavation. This approach is often adopted when installing sensors at shallow depths beneath existing structures (see Figure 5). Where possible, sensor terminations should be housed in inspection wells providing physical access to all connectors. Ideally, these wells should also be equipped with reference benchmarks to enable geodetic surveys. Additionally, the wells can serve as junction points for connecting sensor segments and as access points for maintenance activities, such as cleaning optical connectors or securing optical splices.

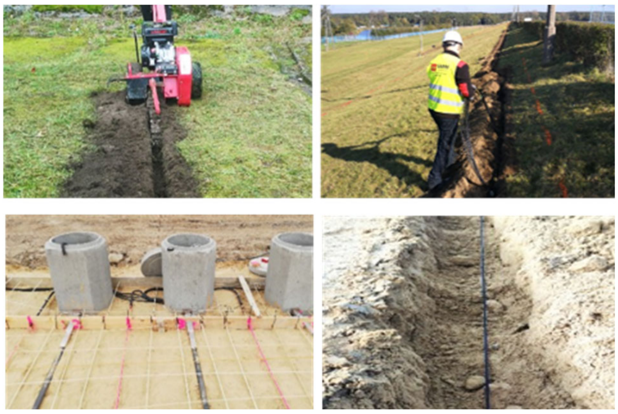

Figure 5. Example installations in earth structures (in wide excavation, narrow trench, sensors end protected in concrete well).

All installation works should be thoroughly documented, with particular attention given to comprehensive photographic records. In particular, any local events or changes in conditions should be described and correlated with the optical length of the sensor to facilitate accurate data interpretation.

3 APPLICATIONS FOR DISSTRIBUED DISPLACEMENT SENSING (DDS)

Strain is the most commonly measured physical quantity in DFOS systems. However, applications based on other parameters are increasingly being developed. The remainder of this article focuses on displacement, temperature and vibration sensing. The first project concerns an earth road embankment instrumented during construction with a shape sensor known as the 3DSensor (Bednarski et al., 2021) and a reference inclinometer system installed along a 48 m longitudinal section (Figure 6).

Figure 6. Installation of 3DSensor and reference inclinometer system.

Measurements were carried out periodically during both the construction and operational phases of the project. Figure 7 presents example results from a selected stage, recorded by both the DFOS system and the inclinometers, showing a mean difference of less than 0.5 mm. Both techniques were able to identify localised sinkholes (3 mm over 3 m) invisible to the naked eye).

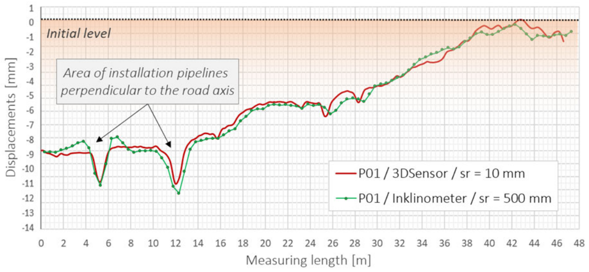

Figure 7. Displacement comparison measured by DFOS (red continuous line) and inclinometer system (green dotted line).

The second example involves sensors installed in selected cross-sections of an earth embankment constructed above a substrate reinforced with concrete columns. During construction, the sensors were stabilised at the sanded base of the embankment (see Fig. 8) and routed to concrete wells located on both sides.

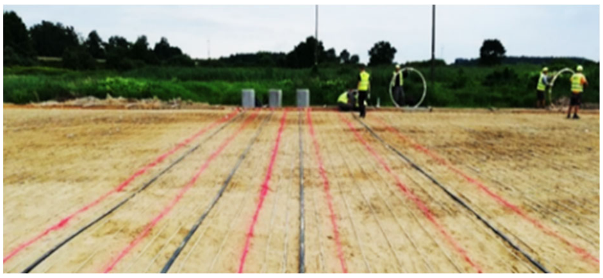

Figure 8. Installation of shape sensors at the embankment base.

The graph below presents example displacements, expressed in millimetres (shape changes), obtained from the sensors and recorded periodically during two subsequent project phases. The DFOS data were correlated with reference geodetic measurements indicating displacements at both the beginning and end of the measurement path.

Interestingly, a spatial resolution of 10 mm over a 21 m section provided 2,100 sensing points per sensor for each measurement. This configuration enabled a detailed analysis of the localised influence of the stiff concrete columns on the embankment's performance. By contrast, the displacement profiles in the areas between the columns remained smooth. The data were subsequently used to analyse in detail the spatial interaction between the embankment and the substrate and to support the development of optimised design procedures for similar structures in the future.

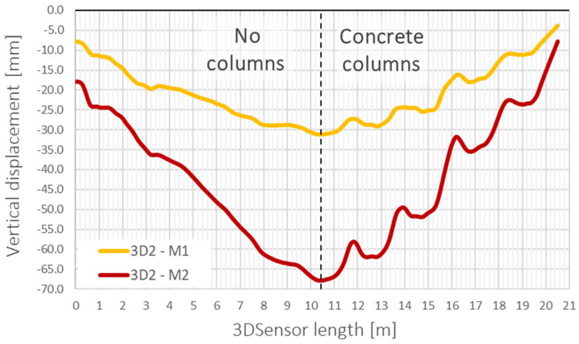

Figure 9. Example displacement profiles registered in two subsequent project phases.

4 APPLICATIONS FOR DISTRIBUTED TEMPERATURE SENSING (DTS)

Temperature measurements using Raman-based systems are frequently employed to compensate for strain readings obtained from other interrogators. The entire procedure can be implemented within a single sensor equipped with two fibres: single-mode for strain and multi-mode for temperature measurements (see Fig. 10). However, DTS systems can also be used as independent diagnostic techniques to detect and analyse temperature-dependent events, such as leakages in dams (thermo-detection method in both passive and active modes using heating cables), leakages in pipelines, or bearing seizure in conveyor belts. In that cases, only one (multi-mode) fibre is actively used during measurements, while the second is use for redundancy or future extensions of the system.

Figure 10. Distributed strain sensor (EpsilonSensor) with two fibres for simultaneous strain and temperature measurements.

The following two examples relate to a relatively new field of application — geothermal energy systems. In the first case, a monolithic sensor with a Raman interrogator was used to support a thermal response test (Figure 11) in a deep (250 m) borehole. Such tests are conducted to determine the thermal properties of the ground, particularly its ability to conduct heat. This information is crucial for the design of ground-source heat pumps and seasonal thermal energy storage systems. The results enable the precise sizing of the ground heat exchanger to the geological conditions of a given site, preventing energy deficits in heating or cooling systems.

Figure 11. The view of the site during thermal response test.

In conventional practice, only the average temperature over the entire borehole depth is obtained; however, DTS measurements allow for a detailed analysis of the temperature distribution, facilitating even more optimised system design. In this example, measurements were carried out over a one-week period, both during the heating phase and the subsequent cooling phase (Figure 12).

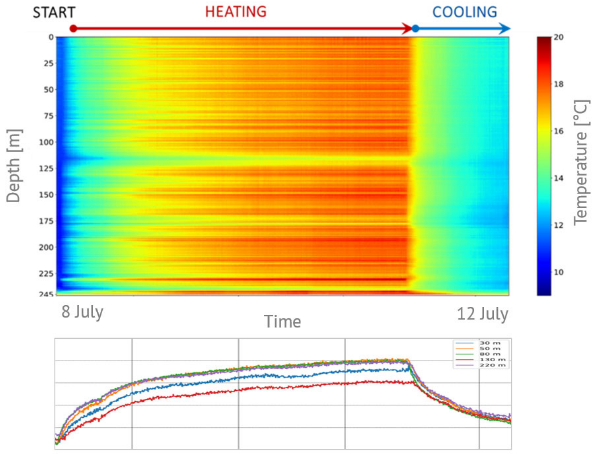

Figure 12. The example temperature result during one week of measurements both in depth and time domain.

In the second case, DTS measurements were used to evaluate the performance of an existing ground-source heat pump system constructed as part of the Józef Piłsudski Museum project in Sulejówek, near Warsaw (Figure 13).

Figure 13. Józef Piłsudski Museum (Sulejówek, near Warsaw).

The total measurement route exceeded 800 m and encompassed four measurement sections within two collectors filled with different grouting materials. One of the objectives of the measurements was to conduct a comparative analysis between these collectors. The measurements were performed over the course of one week during the museum's normal operation. Example temperature results from one section, presented as a function of time and depth, are shown in Fig. 14.

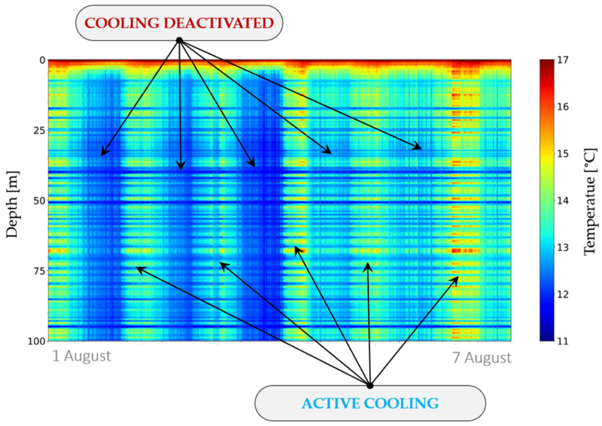

Figure 14. The example temperature result during one week of measurements both in depth and time domain.

5 APPLICATIONS FOR DISTRIBUTED ACOUSTIC SENSING (DAS)

The final group of measurements described in this article concerns Distributed Acoustic Sensing (DAS). Despite its limitation in spatial resolution (typically no better than 1 m), the key advantages of this technique include extremely high sensitivity in detecting strain rate at the level of nε/s, very high sampling frequency (around 50 kHz) and the capability to perform measurements over very long distances (> 100 km). These characteristics make DAS particularly suitable for various types of microseismic analyses and for detecting dynamic sources in the vicinity of the fibre-optic route, including interactions caused by unauthorised third parties. The following projects focus on these two application areas.

The first project concerns microseismic diagnostics of an earth dam in a reservoir supplying a power plant. A total of 1,320 m of sensors were installed along the upstream and side sections, including sensor segments placed in trenches. In addition to vibration monitoring, the project also investigated the potential of an active thermo-detection method, which involved installing additional heating cables along the fibre-optic route and performing DTS measurements during heating and cooling phases. This approach enabled the identification of moisture gradients in the soil and, in particular, potential water flows and leakages.

Figure 15. The earth dam equipped with DFOS sensors for distributed temperature (DTS) and acoustic sensing (DAS).

In the context of DAS, micro-vibrations were induced at selected locations along the length of the installation using both a handheld hammer and an automated, repeatable seismic vibrator mounted on a moving vehicle. The dynamic response of the sensor integrated within the earth structure was recorded, and characteristics (e.g. speed) of propagating wave were analysed in detail. This approach enabled the assessment of the structural integrity of the earth dam, including the degree of ground layer compaction, possible voids and cavities, as well as water level and moisture conditions associated with potential leakage risks. Importantly, analogous measurements were repeated at different time intervals to allow comparative analyses and to identify potentially hazardous zones where the monitored parameters exhibited the greatest temporal changes.

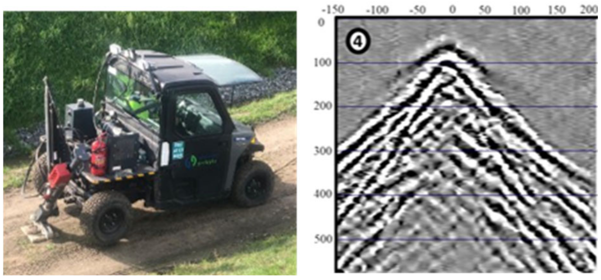

Figure 16. Seismic vibrator and example DAS signal.

The knowledge and experience gained from this project proved highly valuable in the context of the significant floods that occurred in Poland in autumn 2024, which damaged numerous strategic earth and hydraulic structures. Many of these structures now require further, effective diagnostics to ensure an adequate level of safety.

The final example concerns the analysis of simulated dynamic sources along an existing 140-metre section of gas pipeline. For this purpose, existing telecommunications cables (already placed in ducting) were utilised, and dedicated monolithic EpsilonSensors were additionally installed both directly in the ground and within ducting, enabling a direct comparison with telecom cable. All three sections (telecom cables in ducting, sensor in ducting and sensor in soil) were connected in series to record identical dynamic actions simultaneously and under the same measurement settings. The simulated vibration sources included the multidirectional (longitudinal and transverse to the pipe axis) passages of a pickup truck and an excavator (Figure 17), as well as human-induced actions such as walking, shovelling and striking the ground with a fist. In total, several test scenarios were carried out over the course of a single test day.

On the second measurement day, all experiments were repeated; however, the interrogator was connected to the optical route not locally, as on the first day, but from a distance of 70 km using the existing fibre-optic network. The objective was not only to assess signal quality over long distances but also to test the feasibility of integrating existing telecommunications fibre-optic lines into advanced, large-scale DFOS monitoring systems.

Figure 17. This is the conference logo.

Analysis of the results showed the strongest signal response for the EpsilonSensor placed directly in the ground. Consequently, employing this configuration increases the likelihood of detecting low-intensity dynamic events and extends the distance from which such sources can be identified. The weakest signals were consistently obtained from the cable located in ducting, although it was still possible to identify strong events such as nearby excavator or truck passes. Certain interactions — for example, engine idling or excavator bucket impacts — were either weakly visible or blurred.

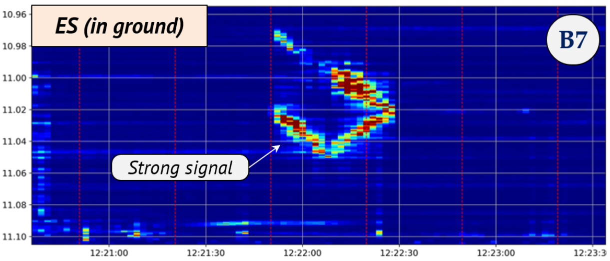

Figure 18. DAS signal recorded by monolithic strain sensor in the ground during the walk of two people (from 70 km distance).

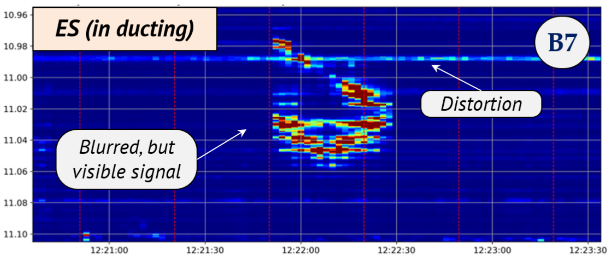

Figure 19. DAS signal recorded by monolithic strain sensor in the ducting during the walk of two people (from 70 km distance).

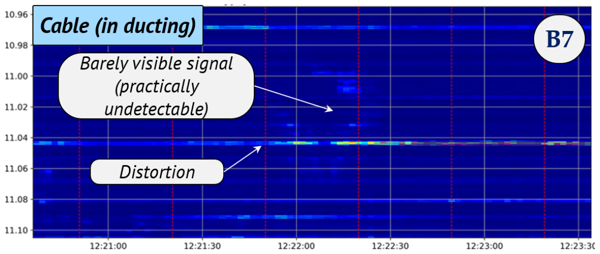

Figure 20. DAS signal recorded by telecom cable in the ducting during the walk of two people (from 70 km distance).

The example results above (Fig. 18 – 20) illustrate a signal recorded during the walk of two people along the gas pipeline (measured from a distance of 70 km). In this extreme case, the cable did not allow for the identification of third-party presence near the pipeline, whereas the monolithic sensors provided interpretable signals.

The conducted experiment clearly demonstrates that, when designing DAS systems, it is essential to precisely define the expected functionality of the system and determine which types of dynamic signals must be detectable. While the use of existing telecommunications networks is convenient and cost-free, in cases where safety is a priority — for example, when identifying the presence of third parties and the risks associated with potential unauthorised activity — it is necessary to install dedicated monolithic sensors. These provide stronger signals and, consequently, more accurate and reliable analyses.

6 CONCLUSIONS

This article summarises the capabilities of DFOS technology for multi-parameter measurements across various earth structures and applications. In addition to conventional strain monitoring, these parameters include displacements (shape changes), temperature and vibrations. Simultaneous measurement of different physical quantities within the same structure is possible using a single sensor equipped with at least two independent sensing fibres. This offers a significant advantage in terms of installation — eliminating the need for multiple sensors — and provides flexibility for future functional extensions of the system. At present, fibre-optic monitoring instrumentation is developing rapidly. By installing sensors in safety-critical infrastructure today, we create opportunities to benefit from future advancements, such as new or improved interrogators, in the near term.

Designing and implementing a system capable of delivering high-quality measurement data is far from trivial. A wide range of aspects must be considered — from the parameters of the sensors and interrogators themselves to installation methods, thermal compensation strategies and post-processing of the recorded data. Nevertheless, this effort is worthwhile, as geometrically continuous measurements can significantly reduce uncertainties — ubiquitous in geotechnical engineering — and thereby enhance the safety of critical infrastructure. The examples presented demonstrate several good practices, illustrative results and the effectiveness of the DFOS technique in selected applications; however, the list of potential uses is considerably longer. At present, the primary limitation to widespread DFOS adoption remains the high cost of interrogators, although this naturally depends on project scale. Given the rapid development of the market, these costs are expected to decrease, while simultaneously the quality and measurement capabilities of interrogators are likely to improve.

7 ACKNOWLEDGEMENTS

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