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# FIBRE OPTIC MONITORING IN GEOTECHNICS – TOWARDS SAFER PILES, EMBANKMENTS, DAMS, AND PIPELINES

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Distributed Fibre Optic Sensing (DFOS) is increasingly applicable in civil and geotechnical engineering to monitor the structural performance during construction and operation. The technology allows for continuous measurement of strain, displacement, vibration, and temperature over the entire length of the sensor – which can extend to tens of kilometres. This makes DFOS technology particularly suitable for monitoring long (linear) geotechnical structures. However, this approach is not plug-and-play. In fact, each project requires an individual design in terms of selecting the sensor and interrogator parameters, installation procedure, compensation methodology, algorithms, and data visualisation techniques to facilitate engineering interpretation. This is why a better understanding of the possibilities and limitations of DFOS, based on practical examples and lessons learned, is of great importance to the industry community. The article briefly discusses four geotechnical cases, where different monolithic sensors were applied to monitor the concrete pile, road embankment, earth dam, and gas pipeline by measuring various physical quantities.

*Keywords*: Distributed Fibre Optic Sensing, Monolithic Sensors, Geotechnical Monitoring, Pile Load Tests, Embankment, Dam, Pipeline.

## 1. Introduction

Distributed Fibre Optic Sensing (DFOS) is used in geotechnical applications (Shi et al. 2021) to measure strains, displacements, vibrations and temperatures continuously over the entire length of the sensing path, making this technology particularly suitable for monitoring longstructures (Zhu et al. 2022). There are three main physical phenomena used in optical interrogators: Rayleigh and Brillouin scattering for strain measurements (Palmieri at al. 2022), and Raman for temperature (Liand Zhang 2022). However, the most crucial element of the system is the sensor integrated with structure. Its replacement orrepairis often challanging or infeasible on site, that is why high-quality, robust and proven solutions should be always selected. Initially, layered cables (Bastianini et al. 2019) were used; nevertheless, their internal debonding and slippage (Howiacki et al. 2023) cause the distortions in strain transfer, increasinguncertainties in data interpretation. That is why monolithic composite sensors were developed (Bednarski et al. 2022). Their different types are discussed in the article: flexible EpsilonSensor for strain sensing in piles (chapter 2), graphite-based EpsilonGraph for temperature and acoustic sensing of earth embankment (ch. 4) and stiff EpsilonRebar for strain and temperature sensing in the pipeline (ch. 5). Monolithic sensors also include the world first 3DSensor(Bednarski et al. 2021) for distributed shape sensing (ch. 3).The case studies briefly discussed hereafterinclude sensors visualizations, photos and data courtesy of SHM / Nerve-Sensors.

## 2. Concrete pile - strains

Strain measurements during pile load tests is a great application for DFOS technique (Hov et al. 2025). In the present case, composite EpsilonSensorfully resistant to alkaline concrete environment and corrosion was installed (Fig. 1). With low elastic modulus (3 GPa), low bending radius (10 cm) and diameter of Ø3 or Ø5 mm, it can be easily tied to the existing reinforcing cages using cable ties. One sensor can form multiple measurement sections, e.g. by looping it at the bottom part of the cage. This approach can reduce the number of active measurement channels (if necessary), but decrease the redundancy. The preferable number of measurement sections along the depth of the pile is four, spaced every 90 degrees within the pile cross-section (if possible). This allows, based on the measured strain distributions, to analyse other mechanical parameters, including cracks, stress and force (knowing or assuming elastic modulus and cross-section of the pile), two-directional bending moments, curvatures and displacements. What is more, separation of strains and the force transmitted by the pile shaft and base is easily achievable, as well as simultaneous distributed temperature measurements (e.g. for thermal compensation during concrete hardening and curing).

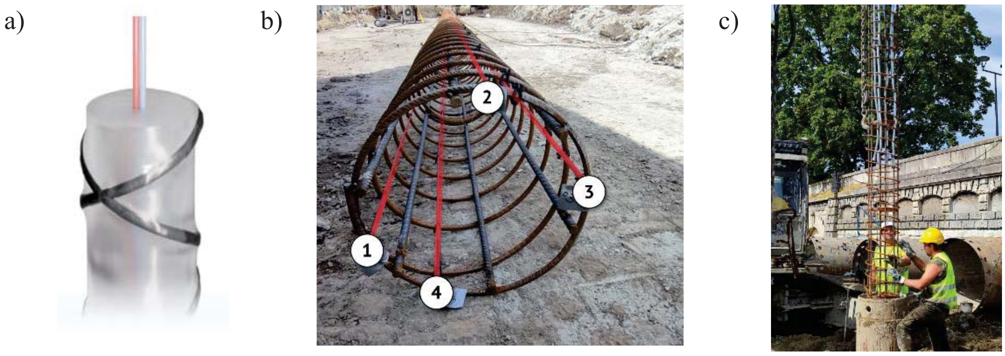

Fig. 1. Application of EpsilonSensor in reinforced concrete pile: a) sensor visualisation; b) mounting to the reinforcing case; c) installation control during construction.

The plots below qualitatively represent example data obtained during pile load tests conducted in Kraków, Poland, in 2024. Based on the four measured strain profiles along the full 18 m depth of the pile, direct analysis of the force distribution and microcrack detection was possible (Fig. 2a). Additionally, by using the relevant post-processing algorithms, vertical shortenings and horizontal displacements (resulting from minor eccentricities) were calculated – see Fig. 2a and 2c, respectively.

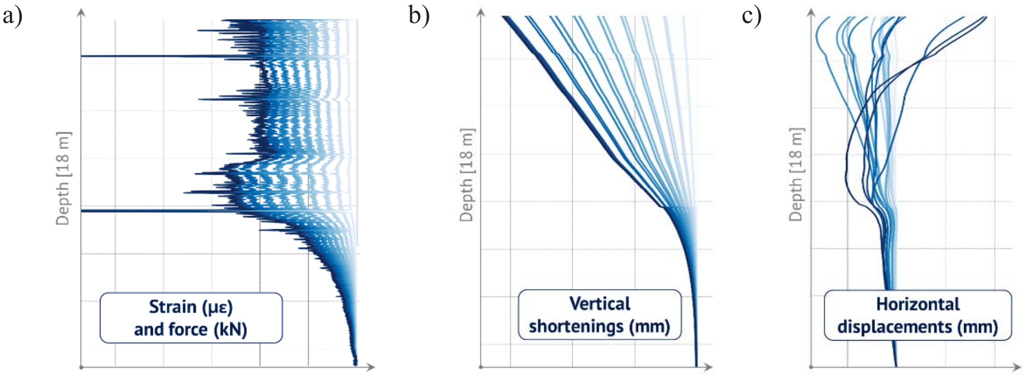

Fig. 2. Measured and calculated distributions of: a) strain and force; b) vertical shortenings; c) horizontal displacements (different lines in the graphs, from light to dark blue, corresponds to the subsequent force values during the loading test).

## 3. Road embankment - displacements

In the second example, 3DSensors were integrated with road embankment to monitor vertical displacements (settlements). The sensor has unique design (Fig. 3a) with four strain sensing fibres arrange at the top and bottom surface of rectangular cross-section. Based on the known and precise spacings between the fibres, it is possible to calculate local curvatures, and then, with adopted boundary conditions, shape changes (both in vertical and horizontal planes). The installation took place during construction (Fig. 3b). Sensors were installed in longitudinal direction of the embankment within the trench filled with sand cushion (Fig. 3c) to minimise the risk of localised pressures or damages by sharp aggregate grains. Periodical measurements were performed during construction, but also after putting the embankment (and road) into operation(Bednarski et al. 2021).

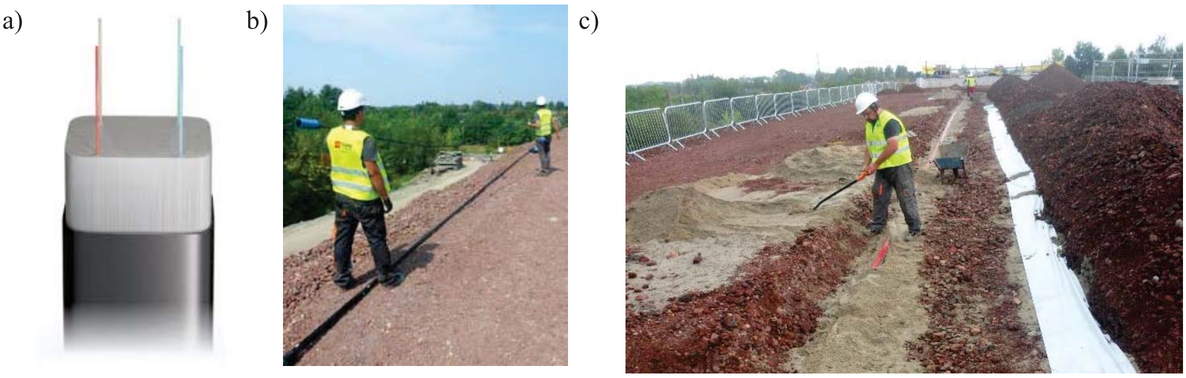

Fig. 3. Application of 3DSensor in road embankment: a) sensor visualisation; b) sensor transportation on site; c) installation within the embankment during construction (sand cushion protection).

As part of the project, reference horizontal inclinometers were also installed along the 3DSensor for validation measurements. Figure 4 presents an example comparison of results from a selected measurement session. The average error between the two independent measurement techniques was 0.5 mm, with the fibre optic sensor being read at a resolution of 10 mm (100 measurement points per metre) and the inclinometer at 0.5 m intervals. This result, achieved under challenging field conditions, confirmed the effectiveness and required accuracy of the DFOS technology.

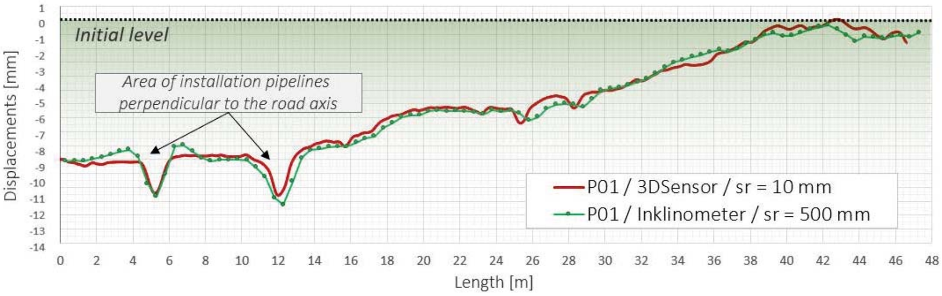

Fig. 4.Displacements (settlements, shape changes) measured by 3DSensor and inclinometer(Bednarski et al. 2021).

## 4. Earth dam - vibrations

The existing earth dam protecting the reservoir used for power plant operation was equipped with EpsilonGraph (Fig. 5a), embedded in a premade trench (Fig. 5b and 5c). The sensor has the same properties as the EpsilonSensor described in Chapter 2 but, thanks to the graphite additive, it has improved thermal conductivity. The goal of the project was to utilise the benefits of two DFOS sub-techniques: distributed temperature sensing (DTS) and distributed acoustic sensing (DAS). DTS was used to detect potential leakages associated with thermal changes. Both passive and active methods (using electrical heating cables) were employed for this purpose.

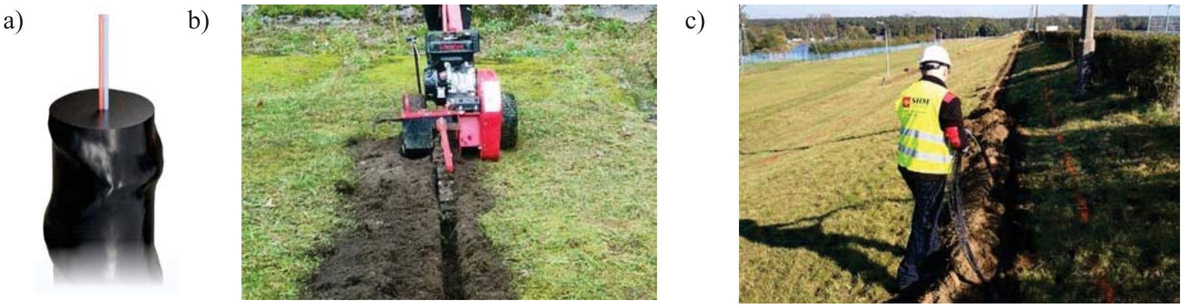

Fig. 5. Application of EpsilonGraph in earthdam: a) sensor visualisation; b) trench along the entire length of the head dam; c) installation of the sensor within the trench.

Dynamic sources comprised manual impacts with a hammer (Fig. 6a) and an automated procedure using a seismic vibrator truck (Fig. 6b). Vibrations (acoustic signals) were recorded by two independent DAS interrogators during short-term simulated tests and a one-week operational period.The collected data, subjected to advanced filtering and analysis, will be used to assess the structural integrity of the dam and identify potentially hazardous zones. Repeating similar studies in the future will enable the analysis of changes in physico-mechanical parameters over time and the assessment of the risk of failure. This is particularly important in the context of the recent floods in southern Poland in 2024, which caused extensive damage to safety-critical geotechnical infrastructure.

Fig. 6. a) Manual vibration source; b) seismic vibrator truck; c) example DAS signal both in length and time domain.

## 5. Gas pipeline - temperatures

The final example concerns the high-pressure gas pipeline equipped with a hybrid monitoring system that synergises the benefits of spot vibrating wire sensors and thermistors with distributed fibre optic sensors. This time, EpsilonRebars (Fig. 7a) were glued directly to the 170m long pipeline section (Fig. 7b) and embedded in the surrounding ground. This is the most robust monolithic strain and temperature sensor available on the market. The measurements included both mechanical strains and temperatures using a DTS interrogator. The aim was to provide possibility of thermal detection of leaks, appropriate strain compensation and, finally, better understanding the overall performance of the pipeline subjected to thermal changes while being constrained by the ground. Measurements were carried out once a month throughout the year. Figure 7c presents example temperature distributions along the entire length for three consecutive months, together with spot reference temperature values. The results demonstrate the high accuracy of DFOS technology and its usefulness in challenging geotechnical applications.

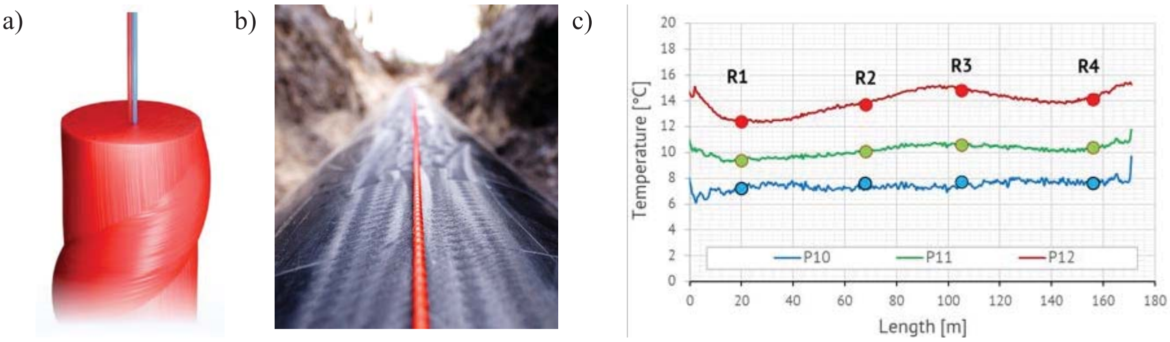

Fig. 7. EpsilonRebar on a gas pipeline: a) sensor visualisation; b) view during installation; c) example temperature profiles measured with DTS over the entire 170 m long sectioncompared to spot thermistors.

## 6. Summary

The versatility of DFOS technology and its adaptability to projects with varying requirements (such as different structures, materials, lengths, installation methods, operating conditions, measured quantities, etc.) is contributing to its growing success in numerous practical applications. The use of high-quality sensors specificallydesigned for engineering and geotechnical purposes, along with a tailored approach to system parameter design, should ensure the required functionality and long-term reliability.

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### References

Bastianini, F., Di Sante, R., Falcetelli, F., Marini, D. and Bolognini, G. (2019). Optical Fiber Sensing Cables for Brillouin-Based Distributed Measurements. *Sensors* 19(23): 5172. https://doi.org/10.3390/s19235172.

Bednarski, A., Sieńko, R., Grygierek, M. and Howiacki, T. (2021). New Distributed Fibre Optic 3DSensor with Thermal Self-Compensation System: Design, Research and Field Proof Application Inside Geotechnical Structure. *Sensors* 21(15): 5089. https://doi.org/10.3390/s21155089.

Bednarski, A., SieĐko, R., Howiacki, T. and Zuziak, K. (2022). The Smart Nervous System for Cracked Concrete Structures: Theory, Design, Research, and Field Proof of Monolithic DFOS-Based Sensors. *Sensors* 22(22): 8713. https://doi.org/10.3390/s22228713.

Hov, S., Meland, H., Helvacioglu, A., Thurner, R., & Wist Amdal, Å. M. (2025). Distributed Fiber-Optic Strain Sensing in Deep Mixed Columns. *Journal of Geotechnical and Geoenvironmental Engineering*, 151(2). American Society of Civil Engineers (ASCE). https://doi.org/10.1061/jggefk.gteng-12825

Howiacki, T., SieĐko, R., Bednarski, A. and Zuziak, K. (2023). Crack Shape Coefficient: Comparison between Different DFOS Tools Embedded for Crack Monitoring in Concrete. *Sensors* 23(2): 566. https://doi.org/10.3390/s23020566.

Li, J. and Zhang, M. (2022). Physics and applications of Raman distributed optical fiber sensing. *Light Science & Applications* 11(1): 128. https://doi.org/10.1038/s41377-022-00811-x.

Palmieri, L., Schenato, L., Santagiustina, M. and Galtarossa, A. (2022). Rayleigh-Based Distributed Optical Fiber Sensing. *Sensors* 22(18): 6811. https://doi.org/10.3390/s22186811.

Shi, B., Zhang, D., Zhu, H., Zhang, C., Gu, K., Sang, H., Han, H., Sun, M. and Liu, J. (2021). DFOS Applications to Geo-Engineering Monitoring. *Photonic Sensors* 11(2): 158–186. https://doi.org/10.1007/s13320-021-0620-y.

Zhu, H.-H., Liu, W., Wang, T., Su, J.-W. and Shi, B. (2022). Distributed Acoustic Sensing for Monitoring Linear Infrastructures: Current Status and Trends. *Sensors* 22(19): 7550. https://doi.org/10.3390/s22197550.