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Distributed strain, settlement and temperature sensing in geotechnical earth embankments

Détection distribuée de la déformation, du tassement et de la température dans les remblais géotechniques

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ABSTRACT: Distributed fibre optic sensing (DFOS) is more and more applicable in civil and geotechnical engineering to monitor the structural performance during construction and operation. The main advantage of this approach is the ability to measure selected physical quantities continuously over the entire length of the sensor – from few millimetres to hundreds of kilometres. This makes DFOS particularly useful for monitoring linear structures such as tunnels, roads, highways, bridges, pipelines, dams or embankments. The article describes the principles of this technique, including its main advantages and limitations, and then focuses on practical applications in several road embankments, including one of the highest in Poland. Depending on the project requirements, the type of the DFOS sensor and the configuration of the whole system, distributed strains, displacements (settlements) and temperatures can be extracted from measurements and analysed in detail. The article summarises a number of good practices and lessons learned on practical issues like selection of the sensor and optical device, installation method, thermal compensation, post-processing algorithms and data visualisation to facilitate its engineering interpretation.

RÉSUMÉ: La détection distribuée par fibre optique (DFOS) est de plus en plus utilisée en génie civil et géotechnique pour surveiller les performances structurelles pendant la construction et l'exploitation. Le principal avantage de cette approche est la possibilité de mesurer des quantités physiques sélectionnées en continu sur toute la longueur du capteur - de quelques millimètres à des centaines de kilomètres. La DFOS est donc particulièrement utile pour la surveillance des structures linéaires telles que les tunnels, les routes, les autoroutes, les ponts, les pipelines, les barrages ou les remblais. L'article décrit les principes de cette technique, y compris ses principaux avantages et limites, puis se concentre sur des applications pratiques dans plusieurs remblais routiers, dont l'un des plus hauts de Pologne. En fonction des exigences du projet, du type de capteur DFOS et de la configuration de l'ensemble du système, les déformations réparties, les déplacements (tassements) et les températures peuvent être extraits des mesures et analysés en détail. L'article résume un certain nombre de bonnes pratiques et d'enseignements tirés sur des questions pratiques telles que la sélection du capteur et du dispositif optique, la méthode d'installation, la compensation thermique, les algorithmes de post-traitement et la visualisation des données afin de faciliter leur interprétation technique.

Keywords: Distributed fibre optic sensing; earth embankment; strain; temperature; settlement.

1 INTRODUCTION

Distributed fibre optic sensing (DFOS) is finding increasing applications in civil (Bado and Casas, 2021) and geotechnical (Shi et al., 2021) engineering. The characteristic feature of that measurement technology and, at the same time, its main advantage, the ability to measure different physical quantities continuously over the entire length of the sensor. These quantities include strain, stress, crack, temperature displacement (Piątek et al., 2023) or vibration (Zhu et al., 2022). Distributed sensing capabilities can directly address one of the main goals and challenges of structural health monitoring (SHM), namely direct local event (or damage) detection. Local events along the measurement path can include, among other things, cracks in concrete, (Howiacki, 2022), leakages in pipelines (Bednarz et al., 2021), sinkholes and settlements in geotechnical structures (Bednarski et al., 2021) or different types of third-party intrusions (Tanimola and Hill, 2009). The distance range can be from a few millimetres to hundreds of kilometres, making DFOS particularly useful for monitoring linear structures (Popielski et al., 2021) such as tunnels, roads, highways, bridges, pipelines, dams or embankments. However, it must be stressed that this is not a plug-and-play solution. The configuration of the system and the measurement parameters should always be tailored to the expectations and requirements of a particular project. The remainder of the article briefly describes the general assumptions and discusses three practical examples of geotechnical embankment applications. Each of the selected case studies concerns the DFOS-based measurement of different physical quantities: strains, temperatures and settlements.

2 SYSTEM CONFIGURATION

In general terms, the DFOS-based system consists of the sensor and the interrogator unit (optical data logger) – Figure 1. Usually, interrogators utilise three main physical phenomena, which are Rayleigh (Palmieri et al., 2022), Brillouin (Bastianini et al., 2019) and Raman (Li and Zhang, 2022) scattering. The first two enable measuring strains (which are the sum of mechanical and thermal effects), while Raman approach is sensitive only to thermal changes. It can be used to compensate the strain results or as an independent diagnostics solution to detect events related to temperature change (e.g. fires or leakages).

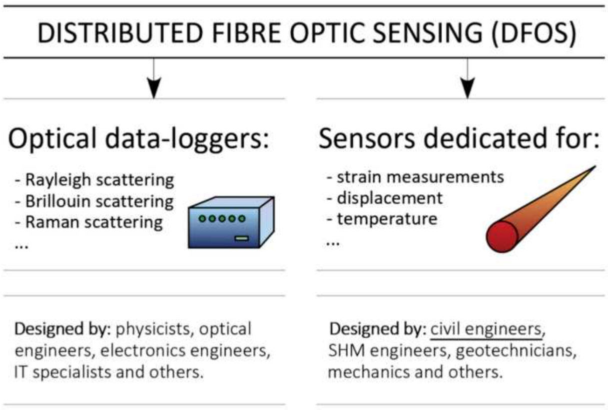

Figure 1. Design of DFOS-based measurement system.

When designing the system, interrogator parameters such as distance range, special resolution, accuracy, sampling frequency or acquisition time should be considered. Although they have a significant impact on the quality of the measurements, the sensors remain the key component of the overall system. Firstly, their long-term interaction with the structure must allow correct interpretation of the results. Secondly, if a data logger fails, it is technically easy to replace. However, this is not possible with long sensors that are permanently integrated into the structure (e.g. embedded in an earth embankment).

The design of the sensor should provide the best possible strain transfer from the structure to the internal optical fibre, which is always the main sensing element. Despite the fact that many commercial solutions are sold for the same purpose (strain measurement), the results obtained may be significantly different (Howiacki et al., 2023). The research shows, that the best performance in Rayleigh-based detection of local events is shown by the monolithic DFOS sensors, in which optical fibre is integrated into composite core without intermediate layers – Figure 2.

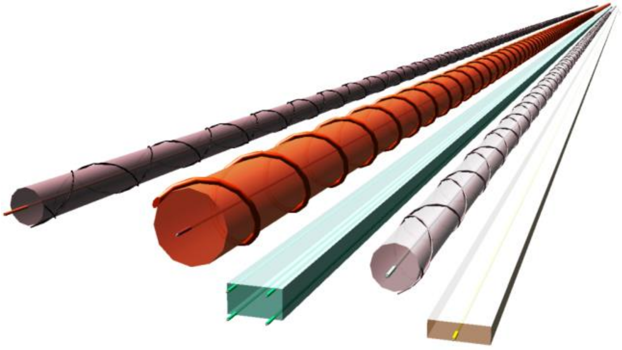

Figure 2. Visualisation of different monolithic sensors.

Although the general idea of monolithic sensors remains the same, some of their parameters can be adapted to the application (Bednarski et al., 2022). These include the shape and size of the cross-section, the stiffness, the number of fibres or the presence of an external braid. For example, in geotechnical applications, high stiffness and robustness are of great importance, whereas for laboratory research, softer and more flexible sensors are desired.

In addition to the interrogators and sensors, other aspects should be considered when designing and creating an efficient DFOS-based measurement system. The most important of these are the installation methods, the thermal compensation approach, the acquisition system, the post-processing algorithms, the data visualisation methods, the interpretation and, finally, the procedures to be followed if an anomaly is detected in the operation of a structure.

In the practical examples of installations and experiences described below, distributed monolithic sensors were used for strain (Nerve-Sensors - EpsilonRebar, 2023) and displacement (Nerve-Sensors - 3DSensor, 2023) measurements.

3 CASE 1 – STRAIN SENSING

The first example concerns an innovative earth embankment that was reinforced at its base with composite rebars. Some of these have been replaced by rigid monolithic sensors, which in this particular case have a dual function in the structure: both sensing and reinforcing.

Figure 3. Monolithic sensor delivered on site in coil.

The sensors were delivered to site in coils (Figure 3) and then stabilised in their intended positions. It should be noted that the installation conditions within the geotechnical structure are very often more challenging for the sensors to survive than those during normal operation - Figure 4. The sensor must therefore be sufficiently robust.

Figure 4. Challenging field conditions during embankment construction.

Figure 5 shows the arrangement of all the DFOS sensors installed within the mesh of the composite reinforcement. There are 6 longitudinal sections (along the embankment axis) of 20 m each and 8 transverse sections (in the lower and upper aggregate layers) of 62 m each. Their exact positions were documented with a geodetic survey immediately after installation.

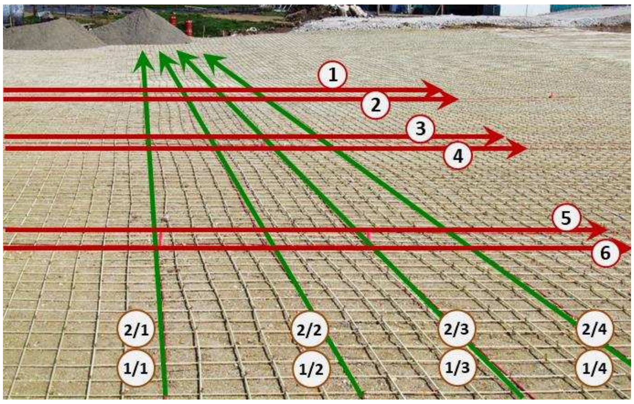

Figure 5. View of the DFOS strain sensors arrangement.

The distributed measurements were carried out as planned during the construction of the subsequent soil layers and after the road embankment had been commissioned. One of the objectives was to estimate strain-based stresses in the reinforcement to assess its effectiveness and compare it with theoretical predictions. Figure 6 shows selected strain profiles measured by one of the longitudinal sensors at subsequent construction stages. The profiles are not uniform along the length and local extremes (stress concentrations) can be clearly observed. These are caused by the uneven substrate and the random stiffness of the heterogeneous aggregate layer.

The strain results were compensated for the thermal changes, which were measured by both a Raman-based device and spot thermistors.

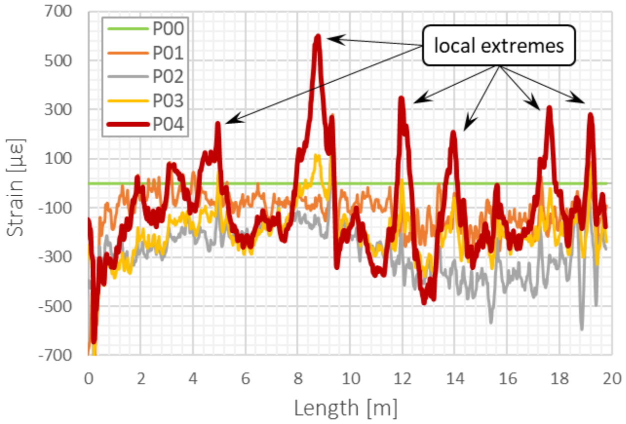

Figure 6. Example DFOS strain results from longitudinal section in subsequent sessions.

It should be noted that the costs of DFOS-based monolithic sensors are negligible compared to the cost of the structure. However, the sensors become an integral part of the earth embankment and can be read at any time. The comprehensive strain results can be valuable during the warranty period and also for long-term assessment of structural condition and health. The durability of the composite sensors is comparable to the lifetime of the structure itself.

4 CASE 2 – TEMPERATURE SENSING

The second case refers to one of the highest road embankments in Poland, exceeding 30 m in some locations – Figure 7.

Figure 7. The view of the road embankment in question during construction.

It was therefore essential to control its deformation during construction in order to ensure efficient work and the earliest possible commissioning. In order to achieve this goal, it was decided to install vertical inclinometers as well as horizontal measurement lines at the base of the embankment, equipped with the following techniques: horizontal inclinometers, hydraulic profilers to measure vertical displacements and, finally, monolithic DFOS-based sensors for temperature distribution control. A typical cross section of the embankment equipped with selected measurement solutions is shown in Figure 8.

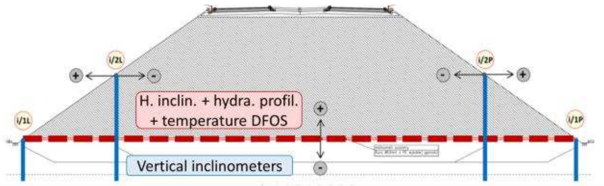

Figure 8. Typical cross-section of the embankment equipped with selected measurement solutions.

The temperature data was used, among other things, to compensate for the readings from two other settlement measurement techniques. All solutions were installed within the HDPE pipe filled with cement-bentonite injection, as shown in the spatial visualisation in Figure 9. The reason for this was that the installation was carried out when some of the soil layers had already been built and compacted. Special cross boreholes were made to allow the installation of the measurement system.

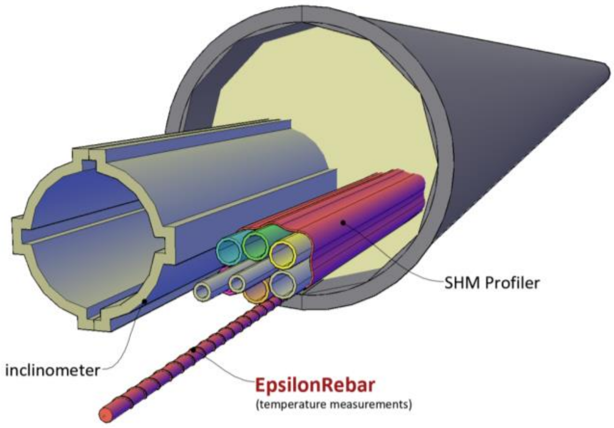

Figure 9. Spatial visualisation of horizontal inclinometer casing, hydraulic profiler and DFOS temperature sensor.

Figure 10 shows example temperature profiles recorded in 20 subsequent readings during one of the measurement sessions. The temperature gradients over length are strictly related to the embankment geometry and they reach more than 10°C along the first 15 m on both sides (influence of slopes). Such large differences can affect the results of settlement measurement techniques and require compensation for correct physical interpretation.

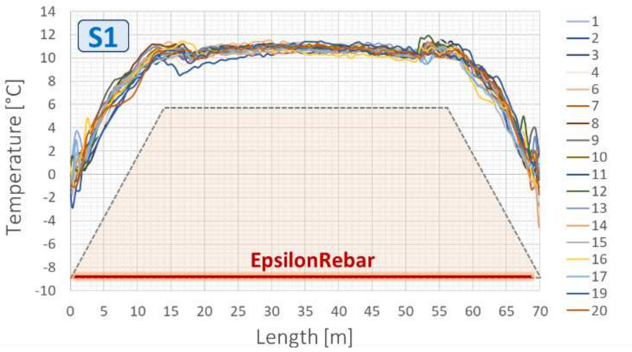

Figure 10. Example temperature distributions in subsequent measurements in reference to the embankment geometry.

Besides the geometry itself, the temperature distribution is also influenced by the current weather conditions, the solar exposure of the slopes and the location of the measurement sections – Figure 11.

Figure 11. Selected locations of measurement cross-sections (S1 – S5) within the embankment - top view.

5 CASE 3 – SETTLEMENT SENSING

The last example focuses on the road earth embankment built over the substrate strenghtened with Controlled Modulus Columns (CMC), as shown in spatial visualisation in Figure 12.

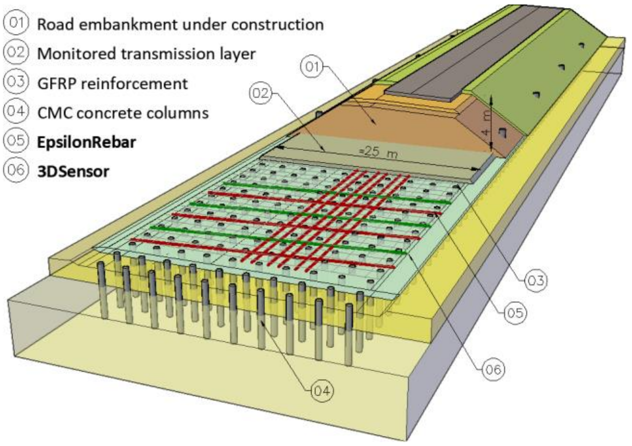

Figure 12. Spatial visualization of the embankment over the substrate strengthened with concrete columns.

Distributed strain and displacement sensors were installed within the transmission layer, both in longitudinal and transverse direction (Figure 13), as a part of GFRP reinforcement mesh. It is worth noting that the transverse sections are not perfectly perpendicular and run through areas directly above the column range as well as between the column ranges.

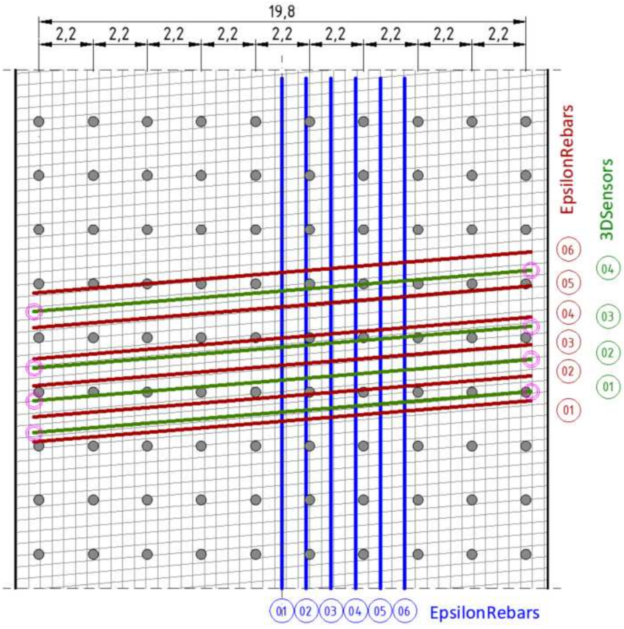

Figure 13. The arrangement of GFRP reinforcement and optical sensors within transmission layer.

The sensors were placed on the ground during construction and then backfilled with successive layers of soil. The installation stage is shown in Figure 14.

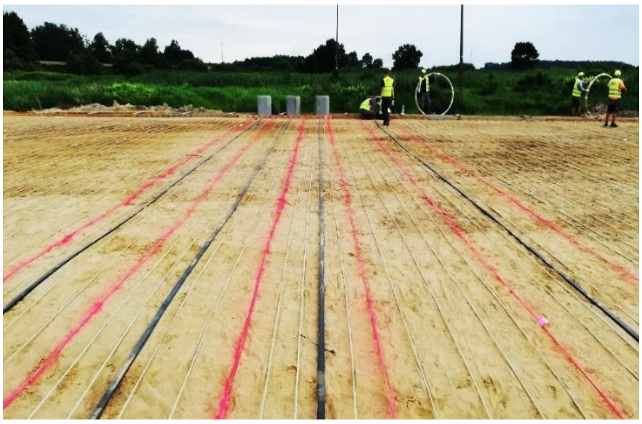

Figure 14. Installation of EpsilonRebars and 3DSensors at the base of the embankment.

The readings were taken during the construction of the embankment according to the planned schedule. An example of the vertical displacements (settlements) of 3DSensor no. 2 is shown in Figure 15. The area between the columns, where the graphs are smooth, and the area immediately above the columns with their local influences on the displacement profiles, can be clearly observed. The boundary conditions (start and end displacement values) were measured by geodetic survey. The 3DSensor internal design allows self-compensation due to the temperature changes in time and length (Bednarski et al., 2021).

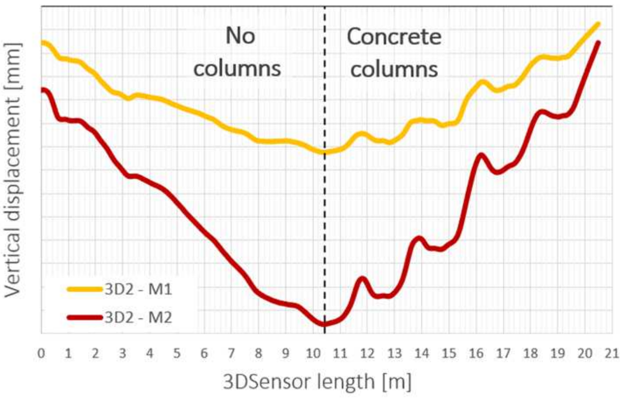

Figure 15. DFOS settlement results from 3DSensor no. 2 in two subsequent measurement sessions M1 and M2.

6 CONCLUSION

The case studies briefly described in the article confirm the versatility of the DFOS technique in monitoring various physical quantities such as strain, temperature or displacement. The ability to acquire distributed profiles makes it suitable and increasingly used for monitoring civil engineering and geotechnical structures. Key challenges include automation and the development of data processing and analysis software.

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REFERENCES

Bado, M.F. and Casas, J.R. (2021). A Review of Recent Distributed Optical Fiber Sensors Applications for Civil Engineering Structural Health Monitoring. *Sensors*. 21(5): 1818. https://doi.org/10.3390/s21051818.

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, Ł., 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, Ł., Sieńko, R., Kanty, P. and Howiacki, T. (2021). New Hydraulic Sensor for Distributed and Automated Displacement Measurements with Temperature Compensation System. *Sensors*. 21(14): 4678. https://doi.org/10.3390/s21144678.

Bednarski, Ł., Sieńko, 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.

Bednarz, B., Popielski, P., Sieńko, R., Howiacki, T. and Bednarski, Ł. (2021). Distributed Fibre Optic Sensing (DFOS) for Deformation Assessment of Composite Collectors and Pipelines. *Sensors*. 21(17): 5904. https://doi.org/10.3390/s21175904.

Howiacki, T. (2022). Analysis of cracks in concrete structures with the use of distributed optical fibre measurements. PhD thesis, Faculty of Civil Engineering, Cracow University of Technology, Poland.

Howiacki, T., Sieńko, R., Bednarski, Ł. 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.

Nerve-Sensors (2023). EpsilonRebar - the world's first monolithic strain DFOS sensor designed for direct embedding into the structural member, concrete or soil. Available online at: https://nerve-sensors.com/product/epsilonrebar/, accessed: 24/08/2023.

Nerve-Sensors (2023). 3DSensor - the world's first shape DFOS sensor for geotechnics and civil engineering, measuring displacements of the structure in 3d space along its entire length. Available online at: https://nerve-sensors.com/product/3dsensor/, accessed: 24/08/2023.

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.

Piątek, B., Howiacki, T., Kulpa, M., Siwowski, T., Sieńko, R. and Bednarski, Ł. (2023). Strain, crack, stress and shape diagnostics of new and existing post-tensioned structures through distributed fibre optic sensors. *Measurement*. 113480. https://doi.org/10.1016/j.measurement.2023.113480.

Popielski, P., Bednarz, B., Sieńko, R., Howiacki, T., Bednarski, Ł., and Zaborski, B. (2021). Monitoring of Large Diameter Sewage Collector Strengthened with Glass-Fiber Reinforced Plastic (GRP) Panels by Means of Distributed Fiber Optic Sensors (DFOS). *Sensors*. 21(19): 6607. https://doi.org/10.3390/s21196607.

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

Tanimola, F. and Hill, D. (2009). Distributed fibre optic sensors for pipeline protection. (2009) *Journal of Natural Gas Science and Engineering*. 1(4-5): 134–143. https://doi.org/10.1016/j.jngse.2009.08.002.

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.

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