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COMPARATIVE ANALYSIS OF DFOS AND TRADITIONAL METHODS FOR SOIL SETTLEMENT MONITORING IN CIVIL INFRASTRUCTURE

Nicola Fabbian
University of Padua, DICEA, Via Ognissanti 39, Padova, 35131, Italy. E-mail: nicola.fabbian@unipd.it

Lorenzo Brezzi
University of Padua, DICEA, Via Ognissanti 39, Padova, 35131, Italy. E-mail: lorenzo.brezzi@unipd.it

Simon Berger
University of Innsbruck, Unit of G.E., Technikerstraße 13, Innsbruck, 6020, Austria. E-mail: simon.berger@uibk.ac.at

Robert Hofmann
University of Innsbruck, Unit of G.E., Technikerstraße 13, Innsbruck, 6020, Austria. E-mail: robert.hofmann@uibk.ac.at

Fabio De Polo
Agency for Civil Protection Bolzano, Via Cesare Battisti 23, 39100 Bolzano, Italy. E-mail: fabio.depolo@provincia.bz.it

Simonetta Cola
University of Padua, DICEA, Via Ognissanti 39, Padova, 35131, Italy. E-mail: simonetta.cola@unipd.it

Accurate estimation of soil settlements in the foundation layer and the structure itself are of paramount importance during and after the construction of a new earth embankment. Various methodologies are currently available for this aim; however, only a few of them provide precise information on the location and magnitude of deformation by measuring within the structure. Distributed Fiber Optic Sensing (DFOS), which is a relatively new structural health monitoring technique, has demonstrated considerable efficacy in the surveillance and early warning of structural performance. Its extensive application in geotechnical engineering is attributed to its capability for conducting continuous and precise measurements along the entire length of the fiber optic cable, making it particularly advantageous for large-scale projects characterized by material heterogeneity. This paper utilizes deformation-detecting fibers exploited with a Brillouin Optical Frequency Domain Reflectometry (BOFDR) to monitor the soil settlements induced by the construction of a new large embankment at Resia Lake (Northern Italy). The embankment, which spans 1.5 km in length and 100 m in base width, was constructed in two phases. Each phase involved a 10 m elevation of soil, primarily composed of sands, completed over two months with a one-year interval between the phases. During this interval, fluctuations in the lake's water level influenced the settlements of the structure. The implementation and evaluation of the innovative DFOS technique evidence that DFOSs are an alternative to traditional methods, such as long-base extensometers, as they provide distributed information over the monitored section permitting the identification of specific layers of significant deformation. This study reports and discusses the results obtained through DFOS and extensometers installed in a 30 m deep vertical borehole. Particular attention is given to the cost-benefit analysis of the methodologies employed, emphasizing the advantages and disadvantages of each tested monitoring technique.

Keywords: Soil settlements; Structural health monitoring; Distributed Fiber Optic Sensing (DFOS); Embankment construction; Deformation monitoring.

1. Introduction

Soil settlements can be evaluated using space-based observation methods or ground-based survey approaches. Space-based methods, including LiDAR, InSAR, GPS, and photogrammetry, are primarily utilized for observing ground movement on a large or regional scale, but they often face difficulties in quantitatively assessing strata deformation and pinpointing specific contributors to subsidence (Zhang et al., 2018). Conversely, borehole extensometers can measure deformation within a single stratum at specific locations. Nevertheless, accurately assessing soil settlement using a single technique remains a challenge due to geotechnical complexities and the inherent limitations of measurement tools. On the other hand, establishing a network of monitoring tools to capture multi-strata deformation can be both cost-intensive and time-consuming. Therefore, identifying a method capable of detecting localized areas with significant deformation at a reduced cost compared to deploying numerous sensors would be beneficial for certain projects. The Distributed Fiber Optic Sensing (DFOS) technique offers the capability to monitor strain and temperature variations along an optical fiber cable and in time. As globally demonstrated by various researchers, DFOS technique shows potential for monitoring soil deformation within boreholes (e.g., Liu et al., 2020). Following this reasoning, the presented case study deals with a DFOS-based monitoring system designed to measure the settlements of a newly constructed earth embankment. The research focuses on the analysis of deformation distribution, presenting DFOS-derived results and comparing them with data obtained from extensometers installed within the same borehole. Additionally, the advantages and limitations of each monitoring technique under investigation are discussed.

2. DFOS for soil settlement monitoring

Distributed Fiber Optic Sensors (DFOSs) offer significant advantages for continuous spatial measurements along an optical fiber cable, providing resistance to electromagnetic interference, long-distance coverage, and precise monitoring of deformations and temperature variations. These sensors are adaptable to different applications, including integration with various civil structures composed of steel or concrete. In geotechnical engineering, DFOSs have been effectively applied in monitoring river levees (Fabbian et al. 2024), earth dam model (Xu et al. 2025), tunnels (Monsberger et al. 2021), piles (Sun et al. 2020), anchors (Brezzi et al. 2024) and many other types of structures. When deployed within a borehole and bonded to the surrounding soil (e.g. Liu et al. 2020), DFOSs enable detailed monitoring of soil layer deformations along a borehole vertical axis, which may result from load changes, consolidation, or other processes. Among the DFOS interrogation techniques available, those based on Brillouin scattering are particularly suited for full-scale applications. These techniques include Brillouin Optical Frequency Domain Analysis (BOFDA) and Brillouin Optical Time Domain Reflectometry (BOTDR). BOFDA requires a closed-loop configuration where both cable ends are connected to the interrogator, whereas BOTDR requires only one end to be connected. The DFOS interrogator (fibrisTerre FTB5020) utilized in this study supports both configurations; however, only BOTDR measurements were here conducted. This approach offers capabilities for cable lengths of up to 25 km, with a spatial resolution less than 1.5 m, a sampling frequency of 0.20 m, and repeatability less than 1 °C or 20 μm. By interrogating the fiber, the Brillouin frequency is measured, varying in magnitude according to the stresses imposed on the fiber. Since Brillouin frequency shift (ΔVb) is influenced by both strain (ε) and temperature (ΔT), temperature compensation is necessary to isolate strain-induced shifts. The Brillouin frequency shift can be expressed as Eq. (1) with $C_T = 2\ MHz/°C$ and $C_\varepsilon = 45\ MHz/\mu\varepsilon$ the strain and temperature coefficients respectively, both obtained in the laboratory. By utilizing only temperature-sensitive optical fibers, independent temperature effects can be subtracted to obtain pure strain measurements. To improve signal noise, multiple BOTDR measurements can be averaged, minimizing variability and ensuring measurement repeatability. When used for strain measurements in a borehole, various fiber optic cables may be employed, including those provided with anchors (Fig. 1a) to enhance grip or cables corrugated along their length. Negative and positive strain values indicate compression and tension respectively, but it is recommended to apply a controlled pre-tension to the cable at installation in order to maintain it in tension even after the compression development. Finally, the settlement of the ground level can be obtained by integrating the fiber optic cable strain along its profile (Gu et al. 2018).

$$\Delta Vb = C_T \Delta T + C_\varepsilon \varepsilon \qquad (1)$$

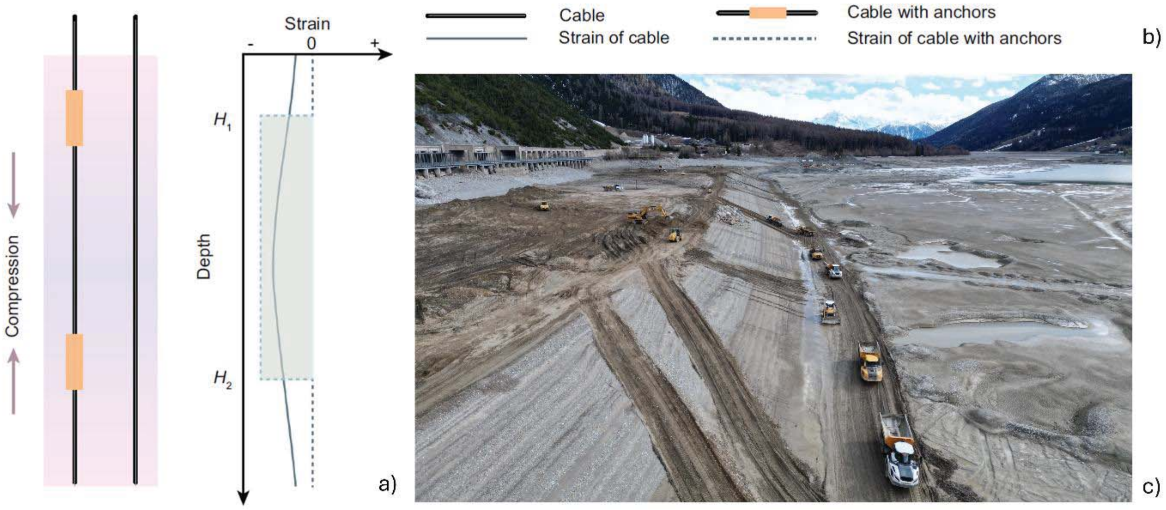

Fig. 1 a) Typical strain distribution of optical fiber cables (Liu et al. 2020); b) Legend of scheme a); c) 2° construction step of Resia embankment on 2 April 2024.

3. Case study and results

Resia Lake, located in northern Italy in the province of Bolzano, was formed in the 1950s with the construction of the Resia Dam. The national road SS40 runs along the lake edge, at the base of a high slope constituted by unstable weathered rocks and screes. The original risk mitigation measures, dating back to the 1960s, have deteriorated: thus, it was decided to distance the road from the slope by constructing a new embankment inside the lake, running parallel to the previous road (Fig. 1c). The embankment, approximately 1.5 km long, 20–23 m high, and 100 m wide at its base, is constructed with material sourced from the lakebed with the aim to ensure the same reservoir volume. The material is a medium sand mixed with pebbles and minor amounts of silt. The total volume of used material is about 2.5 million m³. Construction occurred in two phases: the 1st portion of the embankment, about 10 m high, was completed in spring 2023, the 2nd half in spring 2024 (Fig 1c). This process required a first temporary draining of the lake during the 1st work phase and a subsequent partially refilling at the end of summer 2023 to maintain the water supply of the hydroelectric power plant downstream. After the 1st construction phase, some monitoring systems were installed in specific sections to assess settlements. In the central section, a borehole was drilled to house three extensometers, a deformation monitoring DFOS (Solifos V9), and a temperature monitoring DFOS (Solifos DTS). Before the 2nd construction phase, in April 2024 a containment structure was added to extend the instrumentation to the top of the final embankment (Fig. 2a). Temperature profiles recorded by DTS (Fig. 2b) reveal significant temperature variations (up to 10°C) between 12 and 22 m of depth, mainly due to both the seasonal changes. After the 2° stage construction, which altered the ground cover, in the same span at depth of 12-22m, temperature fluctuations came down to about ±1°C, mainly attributable to the BOTDR instrumentation precision. These temperature variations are accounted to isolate the V9 strain component attributable to thermal effects, thereby improving the accuracy of deformation measurements related to mechanical loading. Fig. 2c illustrates the settlements recorded by the three extensometers alongside the lake water level fluctuations. The extensometers operated continuously from July 2023 to March 2024, deactivated for 2° step construction and, finally, reactivated in October 2024; however, the reactivation established a new reference point, effectively losing the continuity of data from earlier measurements. The settlement data show a period of stability in the initial months after the 1° step construction, followed by a minor swelling during the winter, likely attributable to lake water level raising. As the lake water level was drawn down for the 2° construction step, the settlement increased up to 27 mm, mainly concentrated within the foundation layer below 22 m of depth.

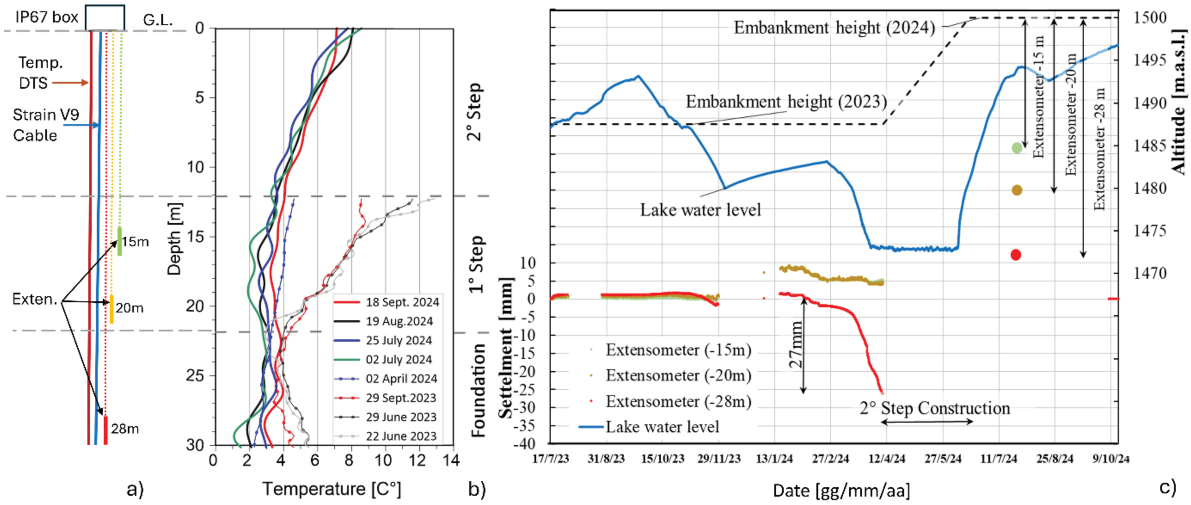

Fig. 2 a) Monitoring set up; b) DFOS Temperature measurements; c) Extensometer strain measurements.

Fig. 3 illustrates the strain profiles obtained using the V9 cable, depicting the average reduction measured with a 20 cm sampling interval and, alongside, the cumulative settlement relative to the borehole base. As the installation was done on 22 June 2023, at the end of 1° construction stage, settlements recorded throughout 2023 were small, in the range of mm, and comparable with the extensometer data. By 2 April 2024, the foundation layer exhibited increasing deformation that is partly due to the additional stress caused by lake level variation. Measurements conducted in 2024, following the 2nd construction step, revealed further settlement increments, due to the consolidation of foundation soils, with cumulative settlement reaching approximately 30 mm. By 18 September 2024, elastic recovery was observed, likely due to the gradual restoration of the normal water level of the lake. The final cumulative settlement is around 24 mm. For the operational structure performance, settlements measured at the completion of the 2nd construction step are of greater significance, as minor settlements recorded in 2023 were offset during construction in spring 2024. Accordingly, Fig. 3 presents the 2024 strain, calculated assuming 2 July 2024 as reference. As the total settlements of 18 mm developed between 2 July 2024 and 18 September 2024 are mainly concentrated in the foundation layer and the strain within the two embankment layers are less pronounced, it is possible to assess that the embankment material was adequately compacted during construction.

4. Discussion and conclusion

The presented case study evidenced some advantages and limitations of the adopted monitoring techniques. Extensometers well measure the temporal evolution of deformation, but their location must be defined beforehand. In contrast, the primary advantage of DFOS lies in its ability to monitor the entire vertical profile, thereby offering a more detailed understanding of settlement distribution. The sensing cables used for DFOS are relatively inexpensive, with the interrogator representing the most significant cost component. Nevertheless, the cost-effectiveness of DFOS improves if the same interrogator is used to manage a large number of measurement points in extensive structures or is shared across multiple test sites. In the presented case, DFOS permitted to monitor also the construction of the 2nd embankment layer, when, instead, the extensometers could not be used. In fact, even if DFOS sensors were temporarily disconnected across multiple phases of a project, they retain their "memory" enabling continuous monitoring. In contrast, traditional transducers lose their initial reference values upon disconnection, restricting their applicability for long-term or phased monitoring scenarios. Finally, precautions must be taken to safeguard the system from potential damage due to the construction activities. In the current setup, DFOS interrogation was manually performed, but automated data acquisition protocols could be adopted if a secure location for the interrogation unit near the monitored site is available.

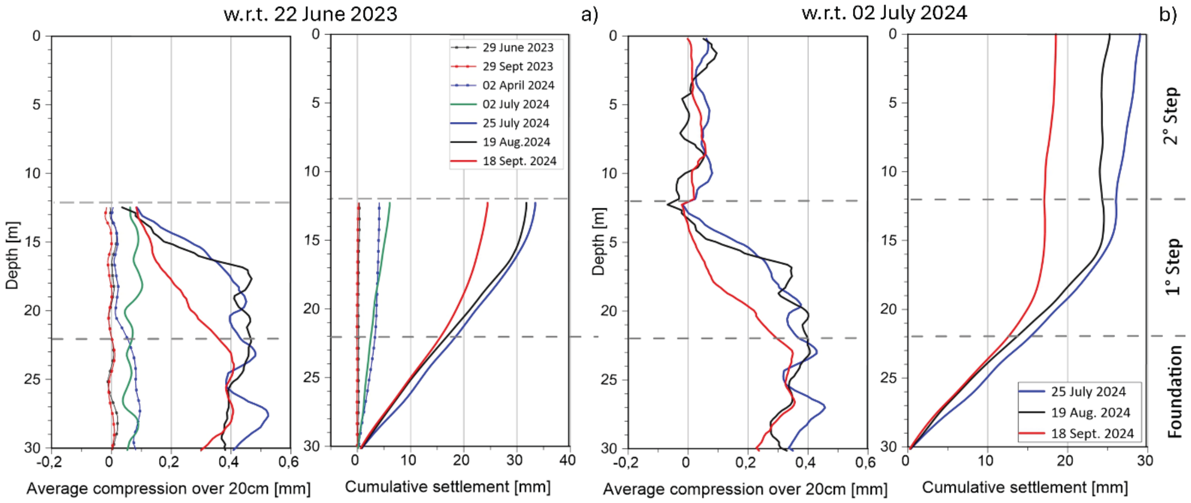

Fig. 3 Average reduction and cumulative settlement, measured with DFOS, with respect to: a) 22 June 2023; b) 2 July 2024.

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