Possibilities of Composite Distributed Fibre Optic 3DSensor on the Example of Footing Pulled Out from the Ground: A Case Study

Rafał Sieńko, Łukasz Bednarski, Tomasz Howiacki, Katarzyna Zuziak, and Sławomir Labocha

Abstract Distributed fibre optic sensing (DFOS) provides breakthrough possibilities in the field of structural health monitoring (SHM) in comparison to conventional spot measurements. It allows the measurements to be registered over the entire measuring length, not only in one point of the structure. That is why this technology is becoming more and more attractive for geotechnics and civil engineering applications, providing both technical and economic benefits. However, to utilize all advantages of distributed sensing it is necessary to apply appropriate sensors, which will be able to accurately reflect the real structural behaviour. This paper discusses in situ application of unique (patented) composite DFOS displacements sensors (3DSensors), which were embedded into the ground layers and compacted around the footing. The research was conducted to observe the potential slip plane generated during the vertical pulling of the footing out of the ground. Distributed measurements were performed to obtain vertical displacement profiles around the footing within the selected ground layers with a spatial resolution of 1 cm. Finally, special visualization of ground deformation in 3D space was performed to analyze in detail the physical changes between the footing and the surrounding ground. No other techniques are currently able to obtain such information, as their application inside the ground layers would disturb its behaviour. The operational rules of displacement DFOS sensor, way of installation, course of the study as well as the exemplary results are discussed hereafter.

R. Sieńko (✉) · T. Howiacki
Cracow University of Technology, Warszawska 24, 31-155 Kraków, Poland
e-mail: rafal.sienko@pk.edu.pl

T. Howiacki
URL: https://www.shmsystem.pl

Ł. Bednarski
AGH University of Science and Technology, Mickiewicza 30, 30-059 Kraków, Poland

T. Howiacki · K. Zuziak
SHM System, Jana Pawła II 82A Libertów, 30-444 Kraków, Poland
URL: https://www.shmsystem.pl

S. Labocha
University of Technology, Katowice, Rolna 43, 40-555 Katowice, Poland

C. Rainieri et al. (eds.), *Civil Structural Health Monitoring*, Lecture Notes in Civil Engineering 156, https://doi.org/10.1007/978-3-030-74258-4_49

Keywords Shape sensors · Strain · Displacement · Optical fibres · DFOS · Composites · Footing · Geotechnics

1 Introduction

1.1 Structural Health Monitoring (SHM)

Nowadays, Structural Health Monitoring (SHM) Systems are an essential and indispensable tool for obtaining information on the operational behaviour of engineering [1] and geotechnical structures [2]. Such systems are usually operated on the basis of automatic sensors installed in real in situ conditions.

The knowledge acquired this way is very important for optimal decision making [3, 4] and improving the safety of critical infrastructure while generating financial savings. These savings should be considered in the context of the entire lifecycle of the structure [5]. Additional in situ measurement information should be used for optimization the designing procedures and standards, calibration of numerical models, verification of theoretical assumptions, controlling the structural behaviour during long-term operation with changing external conditions and finally managing the maintenance of the structure (including renovation strategies)—see the scheme in Fig. 1.

The need for performing in situ measurements results from many factors, including the construction law and standard requirements [6, 7], but the most important are the physical ones related to uncertainties arising from:

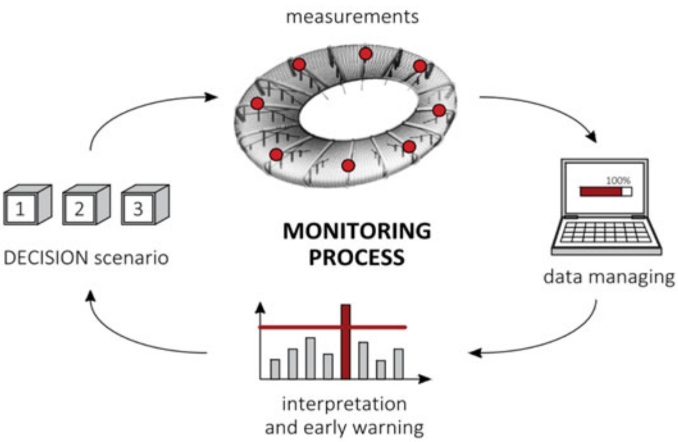

Fig. 1 The simplified scheme of the structural health monitoring process

- material's heterogeneity and associated random variations in its physical and mechanical parameters (e.g. strength, elasticity modulus, coefficients of thermal expansion, etc.),
- geometrical imperfections and tolerances (deviations from design, idealized assumptions),
- random actions and loads (there is always a probability of occurring over-standard values),
- time-dependent effects (e.g. creeping, shrinkage, fatigue), which are very difficult to predict with required certainty,
- cyclic loads and changing external conditions (e.g. temperature, ground humidity, barometric pressure, etc.),
- assumed theoretical simplifications and idealized models applied during designing stage,
- the pressure of time and money that usually accompanies the investments and increases the risk of human error at every stage of the process (design, construction, exploitation and maintenance).

  It is worth to underline that the number of the above factors are particularly important for geotechnical structures, where uncertainties regarding the ground parameters are much higher than in standard (cubature, overground) civil engineering applications. The ground parameters may differ significantly depending on their location and what is more, they are changing over time with the changing external conditions (e.g. the humidity).

1.2 Distributed Fibre Optic Sensing (DFOS)

Due to the increasing number of applications in the field of structural health monitoring systems and taking into account the complexity of this problem resulting from the above-mentioned factors, the new measurement solutions are constantly being sought. The main goal is to provide comprehensive and reliable structural information while keeping the system cost-effective. The newly-designed solutions should focus on early detection of local damages or defects [8], which could bring measurable financial savings and improve safety.

Nowadays, one of the most promising technologies in this context is distributed fibre optic sensing (DFOS) [9], which, in contrast to spot measurements, allows to perform measurements in geometrically-continuous way along the entire length of the optical fibre (see Fig. 2). When using conventional spot sensors, there is always a high uncertainty about what is happening between them and even advanced mathematical models are not able to compensate for this uncertainty. On the other hand, the use of multiple spot sensors at the same time (quasi-distributed measurements) is usually economically and technically not justified. Thus, distributed sensing over distances from several millimeters [10] to even hundreds of kilometers [11], can be considered as a completely breakthrough solution.

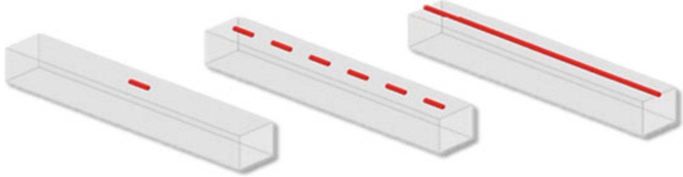

Fig. 2 The scheme of the measurements: spot (left), quasi-distributed and distributed (right)

The optical sensor, in which measuring element is the optical fibre, can replace thousands of conventional spot sensors, depending on the applied spatial resolution and measuring distance (usually from 100 to 5 measuring points per one meter of the sensor). This creates completely new possibilities for the assessment of technical condition of different types of engineering and geotechnical structures.

Performing measurements of selected physical quantities (usually strains or temperature) in a distributed way is possible thanks to utilizing different optical phenomena, like Rayleigh [12], Brillouin [13] and Raman [14] scattering. Each approach is characterized by its own advantages and disadvantages and should be chosen individually depending on the requirements of a given installation. For example, Rayleigh scattering, due to its high spatial resolution, is adequate for precise measurements with localized events over the length of tens of meters, while Brillouin scattering is usually applied for km-range measuring distances, but with worse spatial resolution.

Another important aspect is the appropriate construction of the sensor itself, which should allow to utilize all benefits of the DFOS technology. Appling the sensor which is susceptible to plasticity effects or which is constructed with layers (analogously like cables) causing the debonding or slippage effects, may invalidate the correct measurements and lead to wrong decisions.

The concept and implementation of the monolithic, composite DFOS sensor (the 3DSensor) dedicated for measuring displacements (changes in shape) is presented and discussed hereafter. The article describes the practical application of this solution within the geotechnical field research, where the footing foundations were pulled-out from the ground.

1.3 Research Problem

Research work was carried out within the framework of the project realized by ENPROM Sp. z o.o. [15], NCBIR No. POIR.01.01.01-00-0789/17, entitled "*Elaboration of the new series of types of transmission towers 400 kV and suitable for them foundations, in this of foundations to the use on grounds about particularly disadvantageous geotechnical parameters*". This project used 400 kV transmission towers and varying shallow foundations with increased pull-off capacity. During

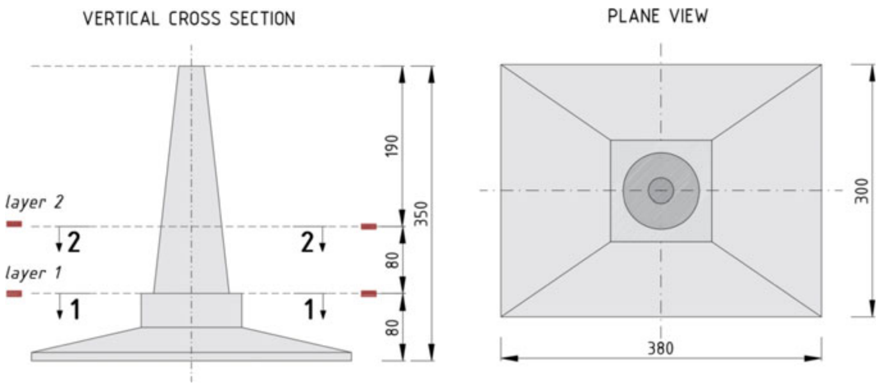

Fig. 3 The cross section and plan view of the exemplary footing investigated during research

the realization of the project, different types of footing foundations were investigated (see example in Fig. 3), including prefabricated special overlay plates, hybrid monolithic-prefabricated special footings strengthened with anchoring micropiles. The uniqueness and usability of the performed research results from the fact that tests were carried out on a full-scale (1:1) objects, in relation to foundations currently used within 400 kV lines.

The project was led in cooperation with the Institute of Roads and Bridges, the Faculty of the Civil Engineering of the Warsaw University of Technology. The structural solutions used in the project were patented and implemented during construction of new important 400 kV transmission lines in Poland, including the lines of the relation Mikułowa-Czarna and Piła-Plewiska-Krzewina.

Another innovative aspect implemented during research was the application of distributed fibre optic sensing for advanced analysis of the cooperation between the footing and the surrounding ground. One of the aims was to observe the ground deformations generated during the vertical pulling the footing out of the ground. Thanks to the application of dedicated 3DSensors, it was possible to determine vertical displacement profiles around the footing within the selected ground layers with a spatial resolution of 1 cm. No other techniques are able to obtain such detailed information, as the presence of traditional sensors inside the ground layers would disturb its behavior and invalidate the results. The operational guidelines of the displacement DFOS sensor, manner of installation, course of the study as well as exemplary results are discussed hereafter.

2 DFOS Measuring System

2.1 Construction of 3DSensor

The basic physical quantity measured with distributed sensing approach is axial strain (με) in the optical fibre. There are number of solutions available on the market (e.g. sensing fibres, cables or DFOS strain sensors) which are dedicated for this purpose. However, in many engineering and geotechnical applications, it would be very favorable to obtain the knowledge about displacements (mm) in the planes perpendicular to the sensor's axis. These displacements represent the change in shape of the monitored structure.

The possibility of converting the measured axial strains into the three-dimensional displacements with practical and reasonable accuracy was investigated in some publications [16–18]; however, their commercial application is very limited. In the research described within this article, the patented (US and PL patents) solution was applied in the form of the composite displacement sensor called 3DSensor. This unique measuring tool was elaborated by SHM SYSTEM company [19] during realization of the research project entitled "*Development of the new fibre optic sensor allowing for the determination of the vertical and horizontal displacements of the studied objects at the distances of up to 120 km*". This project was funded by the grant won at the National Centre for Research and Development within the framework of Intelligent Development Operational Program 2014–2020 (POIR.01.01.01-00-0550/15).

During the design stage, the inventors of the 3DSensor were able to avoid the main limitations and disadvantages of the widely applied DFOS sensing solutions (usually based on the cable production technology). First of all, they did not use plastic and steel to protect the optical fibre, due to their very limited elastic range and plasticity effects, which disrupts the ability to take correct measurements. In the 3DSensor's core a special composite was applied, which allows for the use of the fibre in a wide elastic range without fear of damage. Furthermore, there are no intermediate layers inside the sensor, which usually would cause debonding and slippage effects, not allowing for the appropriate strain transfer. Within the 3DSensor, optical fibres, in their primary coatings, are fully integrated with the composite core during production (pultrusion) stage, creating a monolithic cross-section. Exemplary view of the laboratory and in situ version of 3DSensor are presented in Fig. 4a, b respectively.

The main idea of the 3DSensor solution is to determine the displacement profile based on axial strain measurements. For this purpose, there is a need to apply more than one optical fibre and employ a special algorithm for data conversion (see also Sect. 2.3).

Fig. 4 Composite DFOS fibre optic 3DSensor for displacement (shape's changes) monitoring: **a** laboratory version; **b** in situ version

2.2 *Optical Datalogger*

Today's market offers a wide range of DFOS devices for strain measurements, characterized by many important factors such as: accuracy, resolution, distance range, spatial resolution, frequency of measurement, price and many others. All of these factors have to be carefully taken into account when testing innovative measurement technologies such as the 3DSensor. In the research discussed in this paper, optical backscatter reflectometer OBR4600 from Luna [20] was applied (Fig. 5a) to read the 3DSensors. Because a large number of optical sensors had to be read simultaneously during tests, also optical switch operating with 15 channels was used (see Fig. 5b).

The optical backscatter reflectometer OBR is based on the Rayleigh scattering phenomenon [21–23], which occur in every cross-section of the fibre due to the partial structure of the matter and resulting fluctuations of the refractive index. These imperfections cause the light to scatter in all directions, as well as backwards into the optical device. Finally, the reflectometer determines the positions of all imperfections and calculates their changes caused by both mechanical and thermal strains. The positions of all local imperfections are random but constant for a given fibre and can

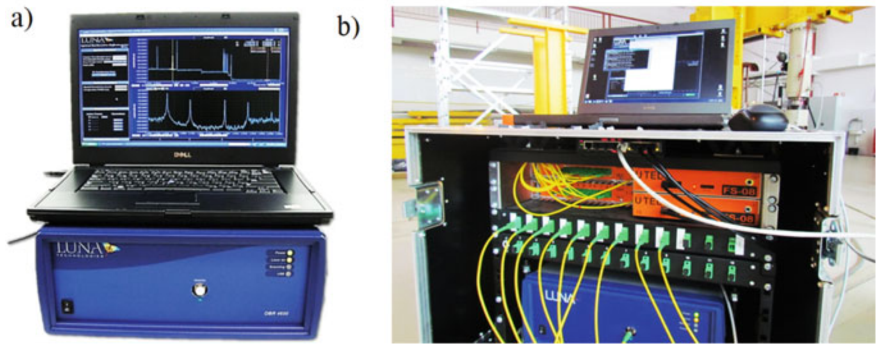

Fig. 5 **a** The view of optical backscatter reflectometer OBR4600 with the software; **b** the view of the reflectometer with optical switch applied during measurements

be compared to a unique fingerprint. By comparing the two patterns (e.g. before and after loading), it is possible to determine strain or temperature changes, which could be expressed by the following equation:

$$-\Delta\upsilon/\upsilon = K_T \cdot \Delta T + K_\varepsilon \cdot \Delta\varepsilon \tag{1}$$

υ mean optical frequency (Hz),
K_T temperature calibration constant (°C^{-1}),
K_ε strain calibration constant (−),
ΔT temperature change (°C),
$\Delta\varepsilon$ strain change (με).

υ mean optical frequency (Hz),
K_T temperature calibration constant (°C^{-1}),
K_ε strain calibration constant (−),
ΔT temperature change (°C),
$\Delta\varepsilon$ strain change (με).

It should be underlined that the final result of the measurement is a linear combination of mechanical and thermal effects. In the research described hereafter, sensors were embedded inside the ground and measurements were performed in short-term, thus there was no need to provide any thermal compensation. The temperature effect could be neglected. It is also worth noting, that the temperature changes are very important during long-term measurements of axial strains. However, the algorithm for displacements calculation is capable of self-compensation due to temperature changes, so even during long-term monitoring there is no need to install additional temperature sensors.

The applied reflectometer software also allows for some measuring parameters to be chosen during post-processing. Optical fibre can be graphically represented by the chain of the individual spot gages as shown in Fig. 6. During data analysis, gauge length (base of averaging the strains) as well as spatial resolution (gauges spacing) should be defined.

Table 1 summarizes selected measuring specifications of the applied backscatter reflectometer and shows the values of parameters chosen for further analysis.

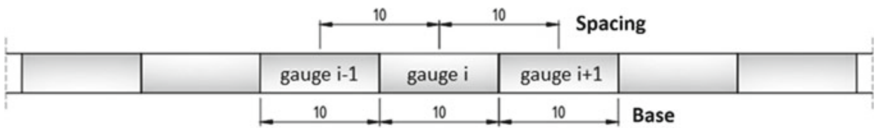

Fig. 6 Graphical interpretation of selected parameters defined during data post-processing

Table 1 Specifications of applied optical reflectometer and post-processing parameters

Heading level	Value	Unit
Distance range (normal mode)	up to 70	m
Strain measurement resolution	± 1	με
Individual gauge length (base)	10	mm
Spatial resolution (gauges spacing)	10	mm

2.3 Algorithm for Data Conversion

The construction of the 3DSensor, as stated before, needs to consist of more than one optical fibre. For analyzing displacements in one plane, at least two fibres are required and for full 3D calculations, at least three fibres. Usually, four fibres are applied to increase accuracy and to minimize the risk of losing data through accidental breakage of the fibre.

Let's consider the simplest situation, were the 3DSensor is used only for measuring vertical displacements, which is the most important factor for many geotechnical and engineering applications (e.g. settlement of embankments, bridge span deflections). The key feature enabling the precise calculation is the very accurate arrangement of the fibres around the neutral axis of the composite core.

The 3DSensor could be represented analogously by the chain of individual gauges (see Fig. 7); however, each individual gauge is now represented by the geometry of trapezoid. This trapezoid is defined by the distance between the optical fibres (approximately equal to the height of the composite core), the spatial resolution and

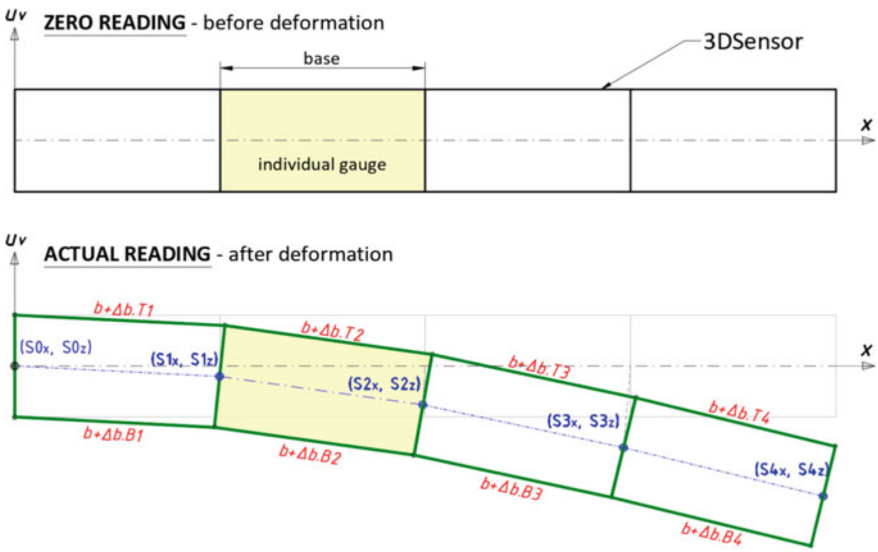

Fig. 7 Graphical representation of the 3DSensor divided into individual trapezoidal gauges

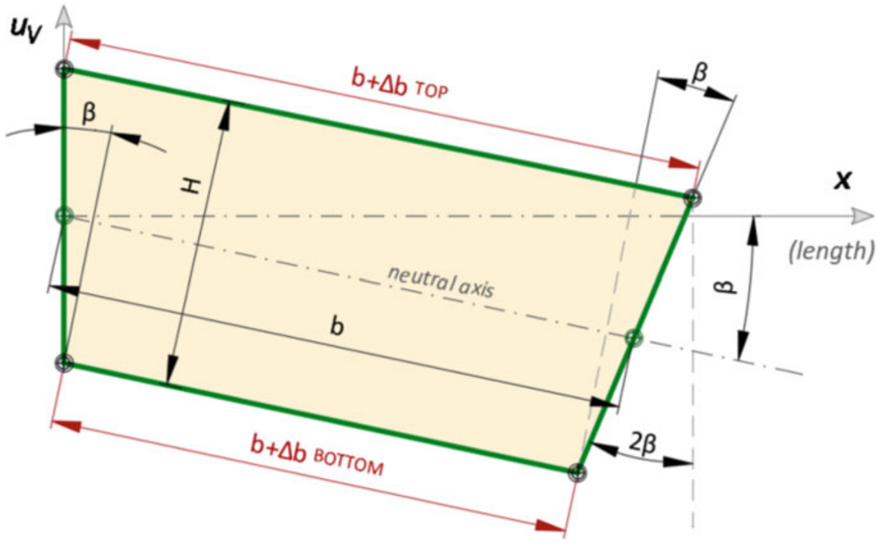

Fig. 8 Trapezoidal geometry of the individual gauge within the 3DSenor

measured strain profiles, causing the elongations and shortenings of the trapezoid bases—see Fig. 8. It is worth noting, that the proposed approach excludes from the analysis all axial effects causing the same changes of the lengths of trapezoid bases. This means that for shape calculations only bending effects are important. Mechanical axial force as well as temperature changes are compensated for by the algorithm.

Finally, the calculated vertical displacement profile depends on the measured strain profiles at the bottom and top surfaces of the composite core, the distance between the fibres (height of the composite core), spatial resolution of applied reflectometer and assumed boundary conditions ("Eq. 2").

$$u_v(x) = f(\varepsilon_B(x), \varepsilon_T(x), H, r, bc) \tag{2}$$

$u_v(x)$ vertical displacement profile (mm) over length,
$\varepsilon_B(x)$ strain profile (με) over the bottom surface of the sensor,
$\varepsilon_T(x)$ strain profile (με) over the top surface of the sensor,
H distance between the bottom and top optical fibre (mm),
r spatial resolution (mm) (base length and spacing of individual gauges),
bc boundary conditions.

$u_v(x)$ vertical displacement profile (mm) over length,
$\varepsilon_B(x)$ strain profile (με) over the bottom surface of the sensor,
$\varepsilon_T(x)$ strain profile (με) over the top surface of the sensor,
H distance between the bottom and top optical fibre (mm),
r spatial resolution (mm) (base length and spacing of individual gauges),

bc boundary conditions.

The boundary conditions should be defined depending on the way of installation. For a free-supported beam, displacements within the supports are assumed to be equal to zero. For the cantilever scheme the displacements and rotation at the first node are equal to zero. In practice, usually the knowledge about displacements in any two points along the sensor is required, which could be obtained from geodetic surveys or through installation the sensor in the areas free from any deformations.

3 Installation and Location of the 3DSensors

The installation process of 3DSensors in ground layers around the analyzed footing is quite fast and comfortable due to their lightweight and easy operation rules. The sensors must be simply placed in the designed positions and covered with the earth, which is further compacted according to standard procedures. There is no need to provide a perfect bonding between the sensor and the surrounding ground—this is one of the main differences between the DFOS strain and displacement sensors. The slippage between the sensor and surrounding medium will significantly disturb strain measurements, but still the shape of the sensor will reflect correctly the shape of the medium. In other words, there is no need to provide bonding between the sensor and the ground for correct displacement measurements.

During research, two measuring layers (planes) were arranged (see spatial visualization in Fig. 9, compare also Fig. 3). The sensors were placed parallel to the footing's edges at 80 cm and 160 cm from the footing's base. The photo from the installation stage, showing the arrangement of the sensors within the second measuring layer, is presented in Fig. 10. The sensors pigtails were protected with the special tubes and led to the mobile measuring station.

4 Experimental Research

4.1 Course of the Study

Altogether, three tests for different types of footings were investigated and this article presents exemplary results in order to discuss the measuring possibilities. However, all the tests had a similar course. The footing was pulled out from the ground through specially designed stand (Fig. 11). The optical measurements were performed step by step with the increasing force (with its fixed values).

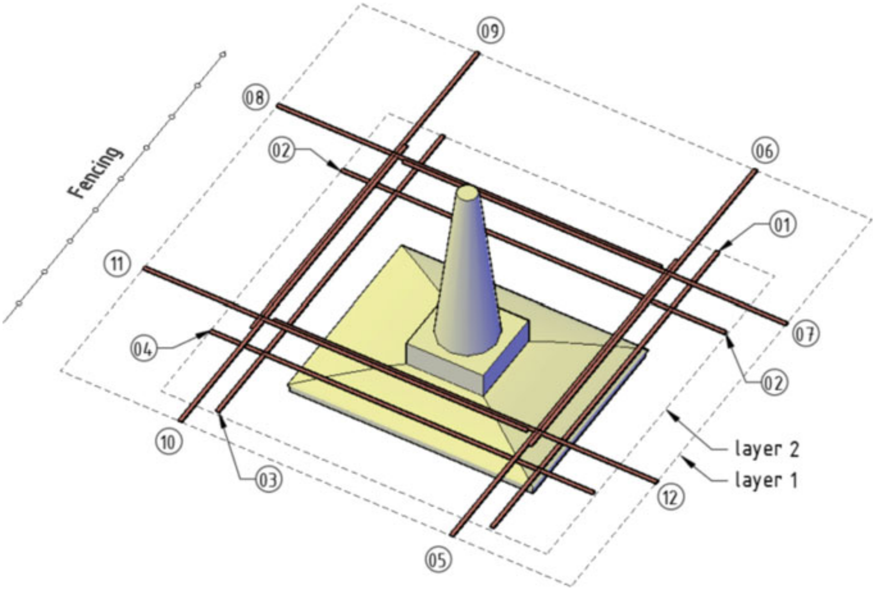

Fig. 9 The spatial visualization of the 3DSensor's arrangement within the ground layers around the analysed footing

Fig. 10 The view of the 3DSensor's arrangement within the second layer: installation stage

4.2 Measured Strain Profiles

In each measuring step, strain profiles at the bottom (lower) and top (upper) surface of the composite core of the sensor were measured with the resolution of ± 1 με. The spatial resolution was set to 10 mm and it means that there were 100 measuring

Fig. 11 The view of the stand for pulling the footing out from the ground

points defined over one meter of sensor. Including all sensors, one can state that during one measurement session almost 10,000 individual gauges were analyzed.

Exemplary raw strain data from the 3DSensor no. S03 are presented in Fig. 12 both for the lower and upper surface. The shape of these plots indicates that both the axial and bending effects influenced the senor's behaviour. Axial tension was caused in this case by the force generated due to the sensor's restrain (friction) caused by the surrounding ground during bending. In the long-term structural monitoring, axial effects are also caused by temperature changes. However, for the shape's change analysis, only bending effects are important, while axial effects can be simply neglected (see Fig. 13).

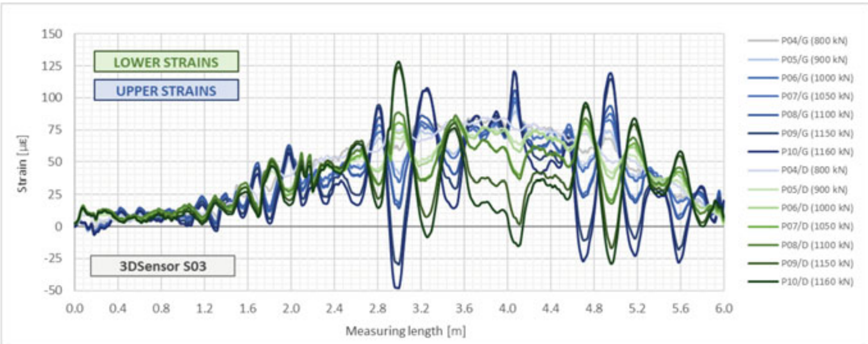

Fig. 12 Exemplary raw strain data from the lower and upper surface of 3DSensor no. S03 coming from both bending and axial effects

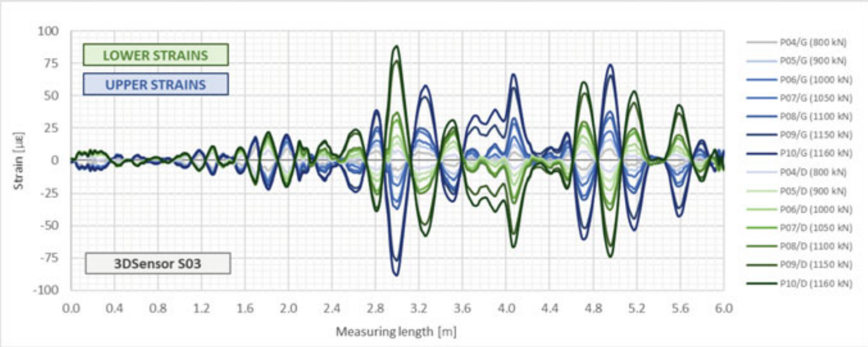

Fig. 13 Exemplary strain data from the lower and upper surface of 3DSensor no. S03 coming from bending effects (with the axial effects excluded)

4.3 Calculated Displacement Profiles

The strain profiles at the lower and upper surface are the input data for the displacement algorithm described in Sect. 2.3. The assumption about boundary conditions was that the vertical displacements at the beginning and at the end of the measuring length are equal to 0. Results are expressed directly in millimeters. Vertical displacements profiles from exemplary measuring stage (at fixed values of pull-out force) are presented in Fig. 13 (top view, plots projected onto the measuring plane) and in Fig. 14 (spatial visualization).

It should be noted that no other reference techniques were applied due to their infeasibility or economical limitations. The presence of massive spot sensors or other methods could significantly disturb the ground behaviour, while flexible composite 3DSensors are do not disturb (reinforce) the ground in any way.

Despite the lack of a reference technique, the accuracy of the proposed solution was verified during a number of laboratory tests and other in situ installations (these will be the subjects of the authors' upcoming publications). For example, the reference horizontal inclinometer system, installed together with the 3DSensor along the road embankment, indicated that the mean difference between these two independent techniques was less than 0.5 mm over a distance of 50 m. The results of the tests performed under laboratory conditions are even better.

5 Discussion and Conclusions

The article presents and discusses the new measurement solution based on DFOS technology and the unique and patented 3DSensor. This solution allows to determine displacement profiles based on the measured strain profiles and is directly dedicated for geotechnical and engineering applications. It could be successfully applied for

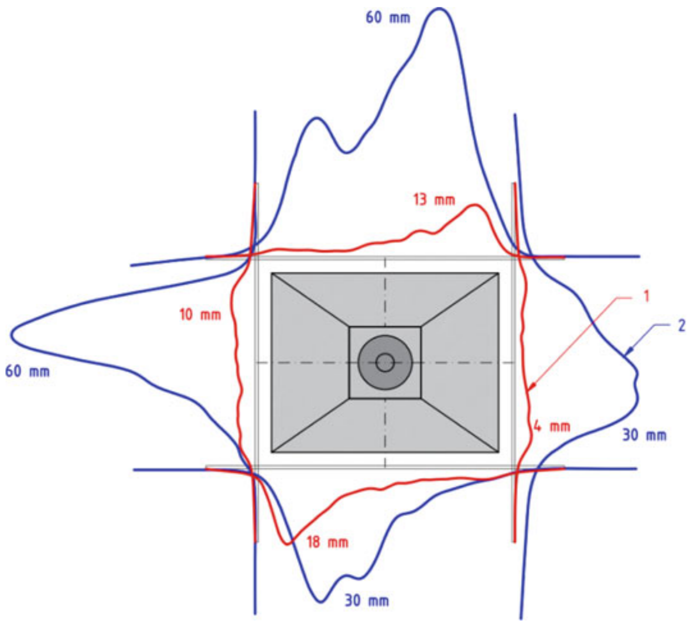

Fig. 14 The view of the exemplary vertical displacement profiles in both layers projected onto the measuring plane: top view

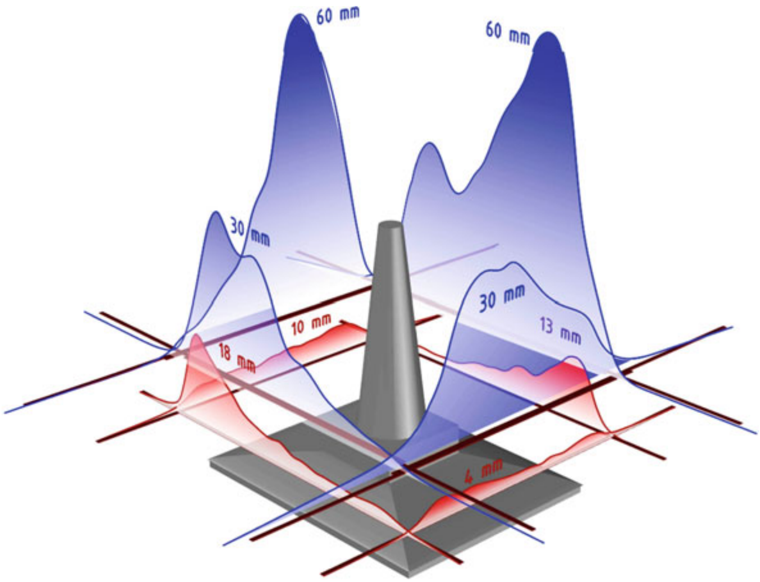

Fig. 15 The view of the exemplary vertical displacement profiles: spatial visualization

bridges, dams, embankments, slurry and retaining walls, roads, highways, pipelines, landslide areas and many others structures. The proposed solution is also suitable for experimental researches, both in the laboratory and in situ conditions.

This relatively simple approach to displacement calculation is based on the challenging production technology of the sensor itself, where the optical fibres are fully integrated into the composite core at the production stage. The key to the innovative technology is the precise position of the fibres in reference to the neutral axis of the composite core. Excessive deviations in position, could cause that the final accuracy of the method to be negatively affected in practical applications. The accuracy of the 3DSensor is guaranteed by an appropriate production regime and quality control.

It is worth noting, that the parameters of the sensor are adjustable depending on the requirements of a given project. For example, the core material and its mechanical properties such as elasticity modulus can be modified (the lower the modulus, the lower the impact of the sensor on the structural behaviour of the monitored specimen or structural member). Another example could be the geometry of the composite core: the higher the sensor's cross-section, the more sensitive the sensor to small vertical displacements.

In this article, world's first unique research was described, showing the proposed measurement solution successfully being applied in a structural test setting. The full-scale footings applied as foundations of 400 kV transmission towers were prepared in a special research field and placed under physical stress. Effects on the surrounding ground layers were studied using the patented 3DSensor technology. One of the aims of the research was to propose an optimal structural solution, which will provide appropriate level of safety and economical benefits at the same time. Distributed fibre optic displacement measurements significantly contributed to this challenging task.

The development of DFOS techniques and measuring tools have resulted in a clear increase in applications in this field in recent years. DFOS displacement monitoring systems were installed in Poland e.g. within:

- industrial, reinforced concrete tower,
- steel and composite bridges,
- innovative smart bridge deck panels,
- road embankments,
- road (asphalt) layers,
- gas pipelines,
- slurry walls and concrete piles (as an alternative for conventional inclinometer system),
- prestressed-concrete slabs and girders,
- composite collectors, and
- other structures.

It should be noted, that the number of the installed displacements monitoring systems is still much lower than the number of systems dedicated for strain measurements. Despite the successfully implemented examples, there are still some challenges that need to be addressed, e.g.: remote and automated measurements within structural health monitoring, clear and useful software for data processing, data acquisition, final accuracy for longer distances and poor spatial resolution (for Brillouin-based systems), long-term stability including the resistance to environmental factors. However, the potential benefits coming from DFOS displacement measurements clearly indicate that this technology will continue to be dynamically developed in the near future.

References

1. Balageas D, Fritzen CP, Güemes A (2006) Structural health monitoring. Wiley-ISTE
2. Dunnicliff J (1993) Geotechnical instrumentation for monitoring field performance. Wiley-Interscience
3. Benjamin JR, Cornell CA (1970) Probability. Statistics and decision for civil engineers. McGraw-Hill, New York
4. Faber MH (2012) Statistics and probability theory in pursuit of engineering decision support. Springer, Berlin
5. Furuta H, Frangopol DM, Akiyama M (2015) Life-cycle of structural systems: design, assessment, maintenance and management. Taylor & Francis Group, London
6. EN 1990: Eurocode—basis of structural design
7. EN 1997-1: Eurocode 7: Geotechnical design—Part 1: general rules
8. Farrar CR, Worden K (2007) An introduction to structural health monitoring. Philos Trans R Soc A 365:303–315
9. Glišić B, Inaudi D (2007) Fibre optic methods for structural health monitoring. Wiley, Hoboken
10. Samiec D (2012) Distributed fibre-optic temperature and strain measurement with extremely high spatial resolution. Photonic International
11. Inaudi D, Glišić B (2010) Long-range pipeline monitoring by distributed fiber optic sensing. J Pressure Vessel Technol 132(1)
12. Pamileri L, Schenato L (2013) Distributed optical fiber sensing based on rayleigh scattering. Open Opt J 7(Suppl-1, M7):104–127
13. Feng Ch, Kadum JE, Schneider T (2019) The state-of-the-art of Brillouin distributed fiber sensing. IntechOpen. In: Liaw SK (ed) Fiber optic sensing—principle, measurement and applications
14. Wang W, Chang J, Lv G, Wang Z, Liu Z, Luo S, Jiang S, Liu X, Liu X, Liu Y (2013) Wavelength dispersion analysis on fiber-optic raman distributed temperature sensor system. Photon Sens 3(3):256–261
15. ENPROM Homepage. https://www.enprom.pl/en/. Last accessed 02 Nov 2020
16. Wu H, Zhu HH, Zhang Ch-Ch, Zhou G-Y, Zhu B, Zhang W, Azarafza M (2020) Strain integration-based soil shear displacement measurement using high-resolution strain sensing technology. Measurement 166:108210
17. Amanzadeh M, Aminossadati SM, Kizil MS, Rakić AD (2018) Recent developments in fibre optic shape sensing. Measurement 128:119–137
18. Zeni L, Picarelli L, Avolio B, Coscetta A, Papa R, Zeni G, Maio CD, Vassakki R, Minardo A (2015) Brillouin optical time-domain analysis for geotechnical monitoring. J Rock Mechan Geotech Eng 7:458–462
19. SHM SYSTEM Homepage. http://www.shmsystem.pl/?lang=en. Last accessed 02 Nov 2020

20. LUNA Homepage. https://lunainc.com/product/obr-4600. Last accessed 02 Nov 2020
21. Güemes A, Fernández-López A, Soller B (2010) Optical fiber distributed sensing—physical principles and applications. Struct Health Monit Int J 9(3):233–245
22. Gifford D, Soller B, Wolfe M, Froggatt ME (2005) Distributed fiber-optic sensing using Rayleigh backscatter. In: European Conference on Optical Communications (ECOC) Technical Digest, Glasgow, Scotland
23. Kishida K, Guzik A (2014) Study of optical fibers strain-temperature sensitivities using hybrid Brillouin-Rayleigh system. Photon Sens (2014)