

# Distributed fibre optic sensing for monitoring soil deformation around piles: Insights from numerical simulations

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**ABSTRACT:** This paper presents the numerical simulations of an experimental test where Distributed Fibre Optic Sensing (DFOS) was embedded within the soil around a large-scale model pile subjected to lateral loads. This study was conducted as part of the GEOLAB project SAM-WT, which aims to advance the understanding of shared anchor piles for floating offshore wind turbines under multi-directional cyclic loading. The experiments were conducted at TU Darmstadt using a hollow, open-ended steel pile with an outer diameter ( $D_o$ ) of 0.324 m, embedded 2 m deep in dense sand. The specific test analysed here applied a monotonic unidirectional lateral load until the pile head displaced by 0.2  $D_o$ , followed by complete unloading, with the goal of evaluating the pile's lateral capacity and the performance of the experimental set-up under simple loading. Alongside traditional instrumentation, an 80 m DFOS cable was embedded in concentric circles around the pile at three depths, providing continuous measurements of longitudinal strain and insights into soil deformations. Due to the novel application of DFOS in sand around piles, a 3D numerical model of the test setup, developed using FLAC3D, preceded the experiments. The DFOS cable was modelled using structural elements whose properties were derived from laboratory traction tests. Initial simulations assumed full coupling between the DFOS cable and soil and were instrumental in selecting the DFOS type and optimising its layout, including the size and depth of the concentric circles, based on anticipated strain distributions. After the experiment, a back-analysis was conducted using updated soil parameters and an elastoplastic cable-soil interface to account for potential slippage effects. Comparison of experimental data with simulations confirms DFOS's ability to provide detailed insights into soil deformations around the pile. These findings deepen the understanding of pile-soil interaction and provide valuable data for validating and refining future numerical models.

**KEYWORDS:** Distributed Fibre Optic Sensing, Numerical Modelling, Pile-Soil Interaction, Floating Offshore Wind Turbines.

## 1 INTRODUCTION

Designing reliable foundation systems remains a key challenge in offshore wind energy, particularly as projects move toward floating structures that rely on anchor piles to resist complex loading conditions. Predicting the lateral response of such piles requires a detailed understanding of the interaction between the pile and the surrounding soil, a relationship that is difficult to fully characterise experimentally using traditional instrumentation.

Distributed Fibre Optic Sensing (DFOS) offers a promising solution by enabling high-resolution strain measurements over long distances. While DFOS has previously been applied to structural components such as pile shafts, its application within the soil mass remains limited (Möller et al., 2023). Yet, direct measurements of soil deformation around the pile are essential for improving models of soil-structure interaction and validating numerical simulations, especially under lateral loading.

This study builds on the experimental campaign carried out within the GEOLAB SAM-WT project (Chalhoub et al., 2024), which aims to enhance the design of shared anchor piles for Floating Offshore Wind Turbines (FOWT). In this context, an innovative DFOS layout was installed in dense Darmstadt sand around a laterally loaded model pile. The DFOS cable was embedded in concentric circles at multiple depths, enabling spatially continuous strain measurements during the test. The experimental layout and instrumentation are described in more detail in Chalhoub et al. (2025a). In this paper, the term DFOS

cable refers to a single optical fibre embedded in a protective coating and used as a distributed strain sensor. The mechanical interaction with the surrounding sand occurs through the fibre's coating. We refer to this as soil-cable interaction throughout the paper for consistency and clarity.

Given the novelty of applying DFOS directly in sand and the challenges in predicting its interaction with the surrounding soil, a 3D numerical model of the experimental setup was developed using FLAC3D (Fast Lagrangian Analysis of Continua in 3 Dimensions), version 7.0. (Itasca, 2019) prior to the physical test. Preliminary simulations assumed perfect coupling between the DFOS cable and the surrounding soil. They were used to guide the selection of the DFOS type and its layout, including the size of the loops and their distribution across multiple depths. After the test, a back-analysis was performed using updated soil parameters and an elasto-plastic soil-cable interface to capture potential slippage – an aspect that cannot be directly measured during experiments.

This paper presents the numerical approach developed to support the experimental campaign conducted at TU Darmstadt. The model reproduces the monotonic lateral loading test (Test 0), simulates the DFOS cable using calibrated structural elements, and investigates how different soil-cable interaction conditions affect the recorded strain. The comparison with experimental data highlights the value of DFOS for capturing soil deformation and the importance of numerical modelling for interpreting such measurements.

## 2 BACKGROUND AND OBJECTIVES

Understanding the response of soil around laterally loaded piles is a longstanding challenge in geotechnical engineering, particularly in offshore applications. The soil's contribution to the overall load-displacement behaviour of the pile is strongly governed by local deformation patterns, which evolve with depth and radial distance. While numerical models have progressively improved our ability to simulate such behaviour, their validation is often limited by a lack of spatially resolved experimental data on soil response.

Most experimental studies to date have focused on instrumenting the pile itself – typically using strain gauges and displacement transducers – without direct access to strain measurements in the surrounding soil. Yet, capturing soil deformations is critical to validating assumptions such as local deformation patterns, rotational mechanisms and the degradation or mobilisation of soil resistance under repeated loads.

While DFOS has shown strong potential in structural monitoring and small-scale centrifuge tests (e.g., Zabatta et al., 2025), its direct implementation within granular soil remains rare (Möller et al., 2023). Recent advances in interrogator sensitivity, fibre robustness and spatial resolution now make such applications feasible.

This study contributes to this growing field by integrating DFOS into a large-scale experimental campaign involving laterally loaded piles in dense sand. The long-term objective is to monitor strain accumulation and redistribution in the soil during multidirectional cyclic loading. However, the current paper focuses on the monotonic loading phase, which serves two essential purposes:

- It acts as a reference to verify the performance of the DFOS layout and assess its sensitivity to soil deformation under controlled conditions;
- It provides a simplified load path that can be replicated in numerical simulations, enabling calibration and exploration of soil-cable interaction mechanisms.

To support and interpret the experimental results, a 3D finite difference model was developed using FLAC3D. The model included structural elements representing the DFOS cable, with mechanical properties derived from laboratory characterisation. Initial simulations were performed assuming a fully coupled soil-cable interface, and served to optimise the DFOS layout and predict the shape and magnitude of expected strain profiles. After the test, a back-analysis was conducted incorporating an elastoplastic soil-cable interface to simulate reduced coupling and sliding effects. This allowed for a more realistic evaluation of strain transmission mechanisms. These numerical simulations, combined with experimental data, provide a structured methodology for interpreting DFOS measurements in granular soils and lay the groundwork for future investigations under cyclic loading.

## 3 EXPERIMENTAL SETUP

Although this paper focuses primarily on the numerical modelling that supported the design and interpretation of this test, a concise summary of the experimental setup at TU Darmstadt is provided for context.

The test employed a hollow steel pile ( $D_o = 0.324$  m,  $L = 3.0$  m, wall thickness  $t = 5.25$  mm) embedded 2.0 m deep in dense Darmstadt sand (relative density  $\sim 89\%$ ). The pile was subjected to monotonic lateral loading, with the head displaced by  $0.2 D_o$  at a controlled rate of 1 mm/min. Conventional instrumentation (strain gauges, LVDTs and a load cell) was used to monitor the pile's structural response.



Figure 1. DFOS cable installation.

However, the originality of the experiment lies in the integration of DFOS within the soil mass, where axial strain in the DFOS cable is measured in response to surrounding soil deformations. An 80 m DFOS cable was installed in circular loops at three different depths, enabling spatially distributed strain measurements around the pile (Figure 1). This configuration resulted from numerical analysis conducted with a 3D numerical model developed in FLAC3D.

Several configurations were tested numerically to identify the optimal positioning and spacing of the loops. The criteria were: (i) maximise strain resolution in zones of high deformation; (ii) maintain axial symmetry to enable multidirectional loading in later stages; and (iii) ensure mechanical compatibility with the interrogator's strain limits.

The final design consisted of three horizontal layers. Each layer comprised three concentric circular loops with radii adjusted based on numerical predictions of radial strain decay. The loops were installed using plywood frames, and the DFOS cable was routed between layers via a protected PVC guide tube anchored along the pit wall.

The DFOS cable had a diameter of 3 mm and an equivalent Young's modulus of approximately 400 MPa, obtained from traction tests. It was interrogated using a Luna ODISI 6100 system based on Rayleigh backscatter. Key DFOS acquisition parameters included: gauge spacing of 5.2 mm, sampling rate of 5 Hz, and a strain range of  $\pm 10,000 \mu\epsilon$ . Reference markers along the DFOS cable facilitated precise localisation of each loop, essential for reconstructing the spatial strain distributions in polar coordinates.

## 4 NUMERICAL MODEL

The numerical simulations aimed to: (i) predict strain distributions around a laterally loaded pile, (ii) optimise the spatial layout of the DFOS cable loops for reliable measurement, and (iii) assess the influence of soil-cable coupling on strain transfer.

### 4.1 General framework

The model was configured to replicate the monotonic lateral loading test conducted at TU Darmstadt. A mesh of hexahedral elements, refined around the pile, was used to model the soil domain. The pile was simulated as a solid cylinder for the sake of model simplicity, with a reduced Young's modulus calibrated to match the flexural stiffness of the actual hollow steel pile under lateral loading. DFOS cables were modelled as embedded linear structural elements arranged in circular loops at three depths, as shown in Figure 2.

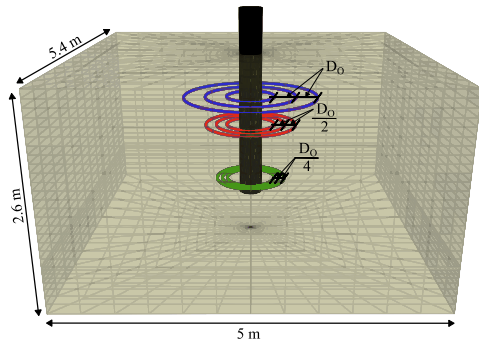


Figure 2. Numerical model using FLAC3D.

#### 4.2 Soil behaviour modelling

To simulate the monotonic loading test, the simplified cap-yield model CHSoil (Detournay et al., 2011) was used to represent the sand. This stress-dependent, non-linear elastic-plastic model is well suited for granular soils and allowed for efficient preliminary testing of different DFOS layouts. The CHSoil parameters were calibrated using triaxial tests on Darmstadt sand from Beroya-Eitner et al. (2024), following the same methodology as in Chalhoub et al. (2023). To analyse the more complex cyclic and multidirectional loading conditions encountered in subsequent tests (Chalhoub et al., 2025b), a more advanced constitutive model will be employed.

The initial numerical model was developed prior to the experiment and was primarily used to optimise the DFOS layout. However, the force-displacement response obtained during the test revealed discrepancies with the pre-test simulations. Therefore, a post-test adjustment of the model parameters was carried out, to optimize the back-calculation of the pile head response observed experimentally. This step was essential to ensure that the numerical strain predictions could be meaningfully compared to the DFOS measurements, as they now reflected a realistic representation of pile-soil interaction under monotonic loading. The re-calibrated parameters, along with their initial pre-test values, are presented in Table 1, while the corresponding experimental and numerical force-displacement curves – before the test and after the back-calculation – are shown in Figure 3.

#### 4.3 Modelling the DFOS cable with structural elements

The DFOS cable was modelled using FLAC3D's structural elements of type pile, which behave as a linearly elastic material and offer built-in interaction springs in both normal and shear directions, making them well suited for simulating embedded systems with soil contact. Each node of a pile element has six degrees of freedom: three translational and three rotational, allowing the elements to capture both axial and bending deformations.

Table 1. CHSoil model parameters from laboratory tests and back-calculation to match the experimental force-displacement response.

Parameter	Symbol	Calibration on laboratory tests	Back-calculation	Unit
Young's modulus number	$E_{ref}^*$	2400	3600	-
Poisson's ratio	$\nu$	0.2	0.2	-
Ultimate friction angle	$\varphi$	43	41	°
Maximum dilation angle	$\psi$	20	11	°
Cohesion	$c$	0	0	kPa
Failure ratio	$R_f$	0.95	0.9	-
Bulk modulus exponent	$m$	0.5	0.5	-
Shear modulus exponent	$n$	0.5	0.5	-

\* $E = E_{ref} p_{ref} \left( \frac{p_m}{p_{ref}} \right)^m$  is the small-strain deformation modulus with  $p_{ref}=100$  kPa and  $p_m$  mean effective stress.

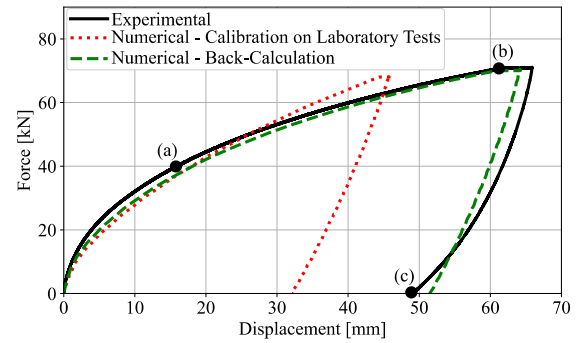


Figure 3. Experimental and numerical force-displacement curves with different CHSoil parameter sets.

Other element types were considered but ultimately rejected:

- Beam elements did not support soil interaction.
- Cable elements lacked interface control.

In contrast, pile elements accounted for both axial and bending deformation, while allowing precise control over soil-cable coupling. Each loop was constructed as a ring of 48 small pile elements, forming a segmented circle. To maintain strain continuity, adjacent elements were connected using pile-pile elastic links with the same properties as the elements, thereby reproducing the behaviour of a continuous cable.

The interaction with the surrounding soil was modelled using pile-soil links. Two interface conditions were considered:

- Fully coupled interface, where the DFOS cable is entirely bonded to the soil. This idealised scenario assumes no relative movement, with the DFOS cable following soil deformations exactly, providing an upper-bound strain response.
- An elastoplastic configuration, where the interface was governed by a Mohr-Coulomb yield criterion. The friction angle was set to 30°, and a cohesion of 15 kPa was used to represent a limited adhesion between the DFOS cable and the surrounding soil. A stiffness of  $10^4$  kN/m was assigned to the interface springs. The incremental confinement option was activated, allowing the shear strength to increase with depth. The normal stress is computed by FLAC3D from the adjacent zones and controls yielding according to the Mohr-Coulomb envelope.

#### 4.4 DFOS Layout optimisation

Several DFOS layout configurations were evaluated numerically:

- Linear arrays allowed localised measurement but were directionally biased;
- Grid layouts captured strain gradients but were complex to analyse under multidirectional loading;
- Circular loops provided symmetric, evenly distributed strain readings and were easier to interpret in polar coordinates.

Based on the simulations, a circular layout with three horizontal layers – top, middle, and bottom – each containing three concentric loops, was chosen for the experimental installation. The depths were selected to capture key features of the soil-pile interaction along the embedded length of the pile:

- Top layer ( $z = -0.6$  m): close to the ground surface where soil displacements are highest, but deep enough to limit excessive cable slippage.
- Middle layer ( $z = -1.0$  m): positioned near the midpoint of the embedded pile to capture intermediate deformation behaviour.
- Bottom layer ( $z = -1.8$  m): located near the pile tip, where deeper confinement effects and toe-kick behaviour are expected to develop.

## 5 RESULTS

In the following, we compare the experimental strain data with numerical results obtained using both fully coupled and elastoplastic interface conditions. The experimental data were rigorously processed to localise the circular sections along the DFOS cable length (further details are provided in Chalhoub et al., 2025a). Longitudinal strains are considered positive in extension and negative in compression.

To visualise the spatial strain evolution across the monotonic loading test, Figure 4 presents polar strain distributions at three key load levels: 40 kN (intermediate), 70 kN (peak), and the end of the test (after unloading). The strains are given in  $\mu\epsilon$ . In each plot, experimental measurements are shown in blue, the fully coupled simulation in red and the elastoplastic interface case in green. Note that the radial scales differ between plots to enhance readability, especially for layers where the strain magnitudes are lower.

Before analysing the strain response, the influence of the DFOS instrumentation on the global behaviour of the pile-soil system was assessed. Simulations conducted with and without the embedded DFOS loops produced nearly indistinguishable pile head force-displacement curves and soil deformation fields, indicating that the presence of the cable had a negligible impact on the overall response.

### 5.1 Polar comparison of experimental and numerical results

Both experimental and numerical datasets exhibited coherent and spatially consistent strain distributions, providing a robust basis for interpreting pile-soil interaction mechanisms. It should be noted that some signal loss was observed in the DFOS measurements under high load levels and during unloading, particularly in the top layer (Figure 4b and 4c).

#### 5.1.1 Radial strain attenuation

At each depth, the simulations successfully reproduced the radial strain gradient observed in the DFOS loops. The highest strains were consistently concentrated in the inner loop, closest to the pile, with a progressive attenuation towards the middle and outer loops. This pattern aligns with theoretical expectations from pile-soil interaction, where soil deformation is most intense near the pile shaft and decays with radial distance. The numerical model accurately captured this behaviour, confirming the effectiveness of the DFOS concentric layout and validating the assumptions on soil-cable coupling conditions.

#### 5.1.2 Depth-dependent behaviour

Depth-wise comparisons revealed distinct strain distributions that evolved with vertical position. In both the experimental and simulated polar plots:

- The top layer exhibited pronounced strains aligned with the loading direction, indicating intense mobilisation of passive resistance near the pile head.
- The middle layer displayed similar but attenuated strain patterns, suggesting reduced resistance mobilisation.
- The bottom layer showed strains oriented on the opposite side of the pile, reflecting a reversal in strain direction consistent with pile rotation and toe kick.

This observation aligns with the experimental strain gauge measurements on the pile, which indicated a rotation mechanism and toe-kick behaviour near 1.6 m depth, demonstrating the coherence between experimental and simulated results.

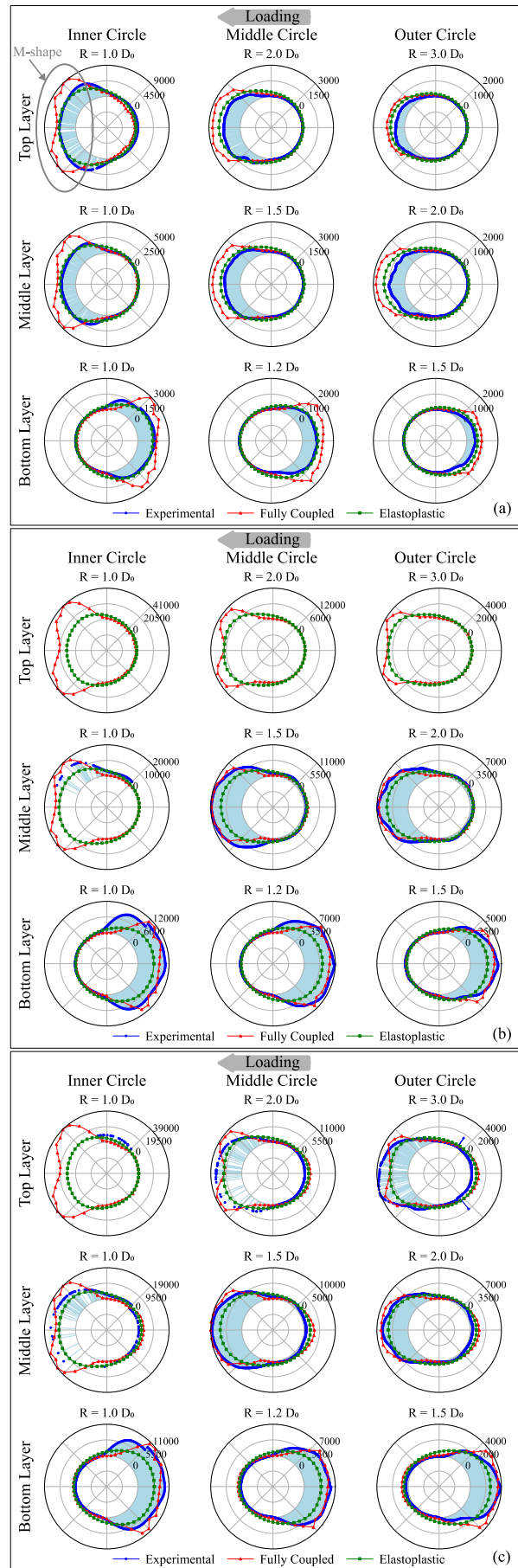


Figure 4. Comparison of experimental and numerical polar strain distributions in  $\mu\epsilon$  at (a) 40 kN, (b) 70 kN, and (c) after unloading.

### 5.1.3 Residual strains and plasticity

Residual strains were evident in the DFOS measurements after unloading (Figure 4c). Although the applied force returned to zero, non-zero axial strains persisted, indicating permanent soil deformation likely due to plasticity and local densification. This behaviour was well captured by the numerical model, which reproduced the location and magnitude of the residual strains with good agreement.

### 5.2 Interface behaviour

The comparison between the experimental DFOS results and the two numerical configurations highlights the importance of accounting for soil-cable interface behaviour.

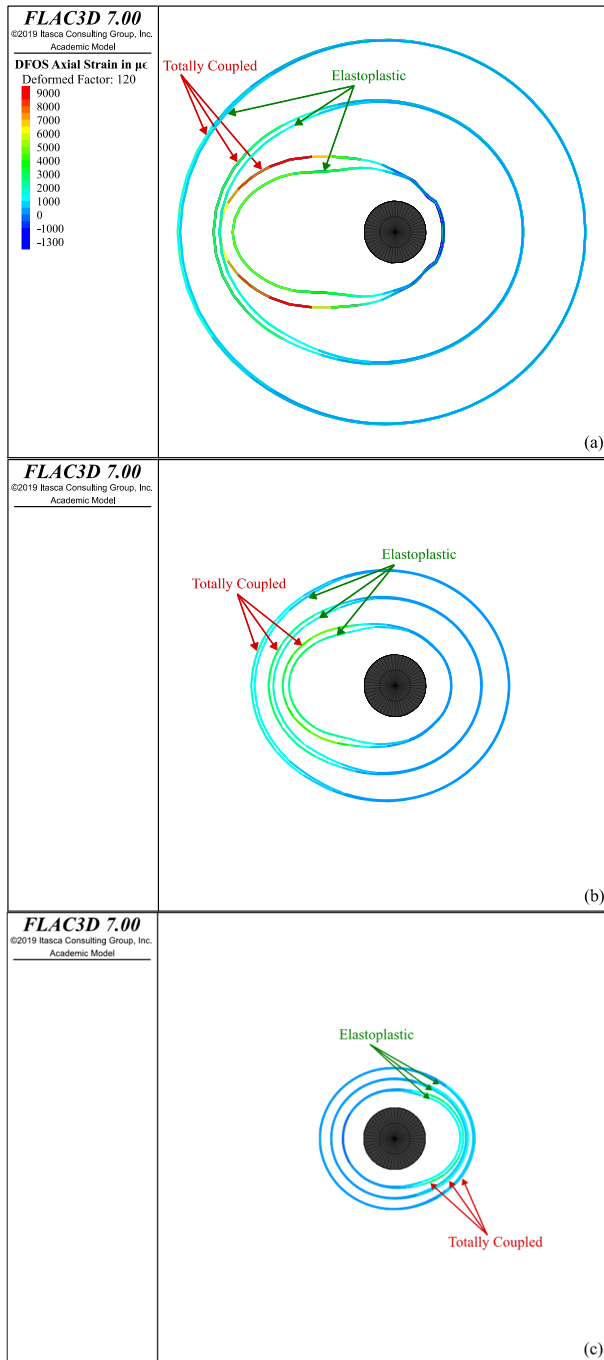


Figure 5. Strain distributions and deformed shapes of the DFOS loops at three depths (a)  $z = -0.6$  m, (b)  $z = -1$  m, and (c)  $z = -1.8$  m, under 40 kN lateral load, comparing the fully coupled and elastoplastic interface models.

In the fully coupled configuration, the DFOS cable is rigidly attached to the surrounding soil, ensuring that it follows the soil deformation exactly. This case typically produces the highest overall strain magnitudes, but not necessarily at the same angular positions as in the experimental data. In particular, the inner loop of the fully coupled model exhibits a distinct M-shaped strain pattern, with two pronounced peaks located around  $\pm 45^\circ$  from the loading direction. These bumps are associated with local maxima in shear deformation and are more prominent near the pile, where displacement gradients are greatest. This shape results from the no-slip condition imposed on the DFOS cable, which forces it to fully follow soil deformations in all directions.

The M-shape pattern is also visible in the experimental DFOS data, though less pronounced. In fact, once strain levels exceed a threshold, slippage occurs between the DFOS cable and the soil, especially in shallow loops. This leads to smoother profiles with maximum strains more closely aligned with the loading direction. The elastoplastic interface configuration replicates this behaviour more realistically. By allowing limited slippage when the interface yield limit is reached, it reflects the decoupling process observed experimentally.

To further illustrate the impact of interface behaviour, Figure 5 shows the strain distributions and deformed shapes of the DFOS cable loops at the three instrumented depths under a 40 kN lateral load, with deformations magnified by a factor of 120. These plots represent the actual shape adopted by the DFOS cable as a result of the imposed soil-cable interaction conditions. Under fully bonded conditions, the cable follows the soil deformation exactly, producing a strain pattern that directly reflects the surrounding soil's response. In contrast, the elastoplastic interface permits relative sliding between the cable and the soil, resulting in a different trajectory and a more realistic strain profile with lower magnitudes.

The difference between the two cases is most pronounced in the inner loops, where the DFOS cable is closest to the pile and experiences the largest soil displacements. At greater radial distances, however, the influence of interface behaviour diminishes. As a result, the cable deforms similarly in both models, and the strain maps tend to overlap in the outer loops, where relative sliding becomes negligible.

### 5.3 Force vs. radial displacement in the loading direction

To quantify soil displacements around the pile, we start from the hoop strain  $\varepsilon_{\theta\theta}$  measured by the DFOS cable, which arises from its circular arrangement. In polar coordinates, this strain is related to displacements by the expression:

$$\varepsilon_{\theta\theta} = \frac{1}{R} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{R} \quad (1)$$

where  $R$  is the radial distance from the pile centre,  $u_\theta$  and  $u_r$  are the tangential and radial displacements. Along the loading direction ( $\theta = 0^\circ$ ), the tangential gradient is assumed negligible due to symmetry, simplifying the relation to:

$$u_r = \varepsilon_{\theta\theta} \cdot R \quad (2)$$

This allows estimation of radial displacements directly from strain measurements. Applying this relation to each concentric loop across multiple load steps, we reconstructed force-radial displacement curves. These curves exhibit the expected non-linear response characteristic of laterally loaded piles. While creep effects during load holds and permanent deformation after unloading were observed in the raw data, Figure 6 focuses on the loading phase only, as the unloading portion was excluded to maintain clarity. Radial displacements were greatest at the inner loops, confirming the attenuation of deformation with radial distance.

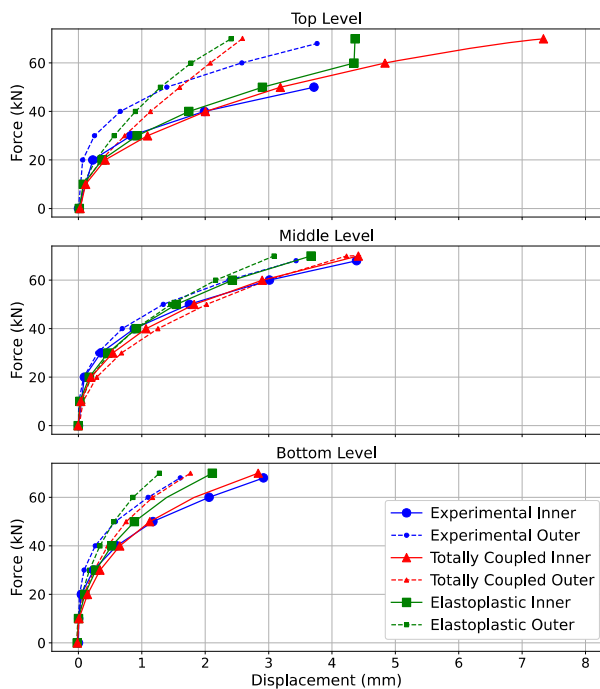


Figure 6. Comparison of force-displacement curves along the loading direction for the inner and outer DFOS loops at each depth.

Variations across depths further support the interpretation of partial rotation and toe-kick mechanisms. Although the displacements are physically oriented in opposite directions at different depths, they are plotted in the same direction for consistent visual comparison.

The numerical results match the experimental data well during the initial loading phase (up to  $\sim 50$  kN), which corresponds to the force levels used in the subsequent cyclic loading phase. This agreement increases confidence in the model's reliability for simulating the cyclic response.

At higher load levels, a slight divergence is observed. The fully coupled model underestimates displacements compared to the experimental data. This is not due to a lack of global deformation, but rather a directional difference: in the fully coupled case, the maximum strains occur at  $\pm 45^\circ$  rather than along the loading axis, due to the M-shaped strain distribution. As a result, the response in the loading direction seems to underestimate the displacement compared to the experimental data, despite higher overall strain levels elsewhere in the model.

For the inner loop of the top layer, where the strain levels are highest, the elastoplastic curve diverges after approximately 60 kN, showing little or no further displacement accumulation. This behaviour results from the yielding of the soil-cable interface links in the numerical model, which decouple the cable from the soil beyond this point. However, this response could not be verified experimentally, as signal loss occurred in this section starting from around 50 kN due to strain levels exceeding the measurement capacity of the system.

## 6 CONCLUSION

This work demonstrates the value of combining Distributed Fibre Optic Sensing (DFOS) and numerical modelling to investigate soil deformation around laterally loaded piles. The numerical model was instrumental in designing the DFOS layout and interpreting the strain measurements obtained during a large-scale laboratory test. Simulations using both fully coupled and elastoplastic soil-cable interfaces reproduced key experimental trends, including radial strain attenuation, depth-dependent mobilisation, and residual strains.

The comparison highlighted the critical role of interface behaviour, with elastoplastic coupling providing more realistic strain patterns and displacement responses. Results also confirmed that sliding effects decrease with radial distance from the pile and are influenced by overburden pressure.

These findings confirm that DFOS cables can be used to monitor soil deformation with high spatial resolution. However, achieving reliable measurements requires careful consideration of the DFOS cable's mechanical characteristics and its interaction with the surrounding soil.

Overall, the study confirms the potential of DFOS for soil monitoring and supports the integration of such measurements in experimental and numerical frameworks. Notably, this work establishes a solid foundation for analysing subsequent cyclic and multidirectional loading phases in the test campaign. A more precise calibration of the soil-cable interface parameters could be achieved by performing dedicated pull-out tests under controlled conditions.

## 7 ACKNOWLEDGMENT

This study received funding from the project "GEOLAB: Science for Enhancing Europe's Critical Infrastructure", as part of the European Union's Horizon 2020 research and innovation programme under Grant Agreement No. 101006512.

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