Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2003

Monitoring of curvature and bending characteristics along ductile driven piles using distributed fiber optic sensing

Christoph M. Monsberger
ACI Monitoring GmbH, Graz, Austria, christoph.monsberger@aci-monitoring.at

Martin Hayden
Keller Grundbau Ges.m.b.H, Vienna, Austria

ABSTRACT: Driven ductile piles are a well-established method in geotechnics to enable a safe and quick solution for economic deep foundations. Their load bearing capacity is separated into shaft friction and toe resistance. Weak soil conditions like lacustrine clay can however limit the shaft friction to a minimum and imply end-bearing piles. Using small diameter piles here can result in buckling and bending under these circumstances, especially in the upper part, where the maximum load is transferred. Compression load tests are usually performed to investigate the impact on the pile behavior, where horizontal displacement profiles along the pile may be monitored using conventional borehole inclinometers. These measurements are not only time-consuming during pile testing, but also requires essential additional efforts for the installation of an inclinometer tube during construction. Distributed fiber optic sensors (DFOS) are advantageous as they can provide the load distribution along the entire structure. The sensing technique usually delivers distributed strain (and temperature) profiles along the longitudinal axis of the installed sensing fiber. If two or more fibers are, however, aligned in a well-known arrangement, multidimensional information can also be captured to derive the curvature distribution resulting from bending orthogonal to the DFOS cable direction. This paper introduces an innovative monitoring setup, consisting of four individual strain sensing fibers to capture curvature and finally, to determine horizontal bending profiles along driven ductile piles. Two different pile types with varying diameter and loading conditions were equipped with the designed system. The test results in comparison to classical inclinometer measurements demonstrate the extensive DFOS capabilities for structural monitoring and their feasibility to improve conventional measurement methods.

KEYWORDS: Distributed fiber optic sensing, ductile driven pile, compression load tests, soil mechanics, curvature monitoring.

1 INTRODUCTION

Efficient and economic foundations are one of the key aspects to ensure the long term integrity of civil infrastructure. The driven ductile pile system provides a safe and quick solution for economic deep foundations as the pile length can be individually adjusted to changing soil conditions. Its load bearing capacity can be separated into toe resistance and shaft friction. While hundreds of piles may be installed at large construction sites, occasional piles are often tested under controlled loading before project start to investigated the bearing capacity, which finally confirms the design and allows pile optimizations. Advanced test setups like the Pile HAY-Proof-System® (Hayden, 2024) also enable a separation of the shaft friction and toe resistance with one test only.

Weak soil conditions however significantly minimizes the shaft friction, implying end-bearing piles. Using small pile diameter might result in buckling and bending under these circumstances, especially in the upper part, where the maximum load is transferred. Compression load tests can help to understand the impact on the pile behavior. These measurements are usually performed using conventional manual borehole inclinometers, but are not only time-consuming during pile testing, but also requires essential additional efforts for the installation of an inclinometer tube during construction. Furthermore, the pile test rig must be accessed each time the measurements are being performed, which implies essential safety hazards for the measurement technician.

Distributed fiber optic sensors (DFOS) have considerably developed over the recent decade for monitoring civil infrastructures, especially in soil mechanics and geotechnics, where their applications range from reinforced earth structures (Moser et al. 2016) to anchor pull-out testing (Fabris et al. 2021) and pile testing (Monsberger et al. 2020). The latter utilizes the distributed sensing feature to monitor the distributed load transfer from the pile to the soil without any gaps, allowing an overall assessment of the pile behavior rather than observing discrete points. The DFOS technology however only delivers strain (temperature) profiles along the longitudinal axis of the installed sensing fiber. Therefore, enhanced design as well as analysis methodologies are required to capture information about the horizontal curvature and bending behavior along the pile.

This contribution introduces the design and realization of an advanced DFOS approach to assess the distributed strain and bending behavior along driven ductile piles. In the following, we shortly describe the construction site conditions, the sensor design and installation as well as the analysis methodology. Moreover, selected DFOS results of the piles with varying diameter and loading conditions are analyzed with respect to geodetic readings at the pile head as well as conventional borehole inclinometer measurements. Finally, the outcomes are discussed and an outlook on further research aspects is given.

2 CONSTRUCTION SITE & SENSING SETUP

Driven ductile piles are a common solution for efficient foundations in the DACH (Germany-Austria-Switzerland) region. The test piles presented in this paper face challenging soil conditions with low-bearing lacustrine clay and silt situated in the upper approx. 15 to 20 m of the embedded length. The piles are designed end-bearing with minimal shaft friction capabilities, where the end length is determined by the penetration speed during driving as shown in Figure 1 (top).

Two different compression-grouted pile types with diameters of 118 mm (PP02) and 170 mm (PP01) are installed for testing purposes. Immediately after pile installation, a conventional borehole inclinometer tube is inserted into the liquid concrete in the inner cavity of the pile, which enables horizontal displacement monitoring later during testing. The DFOS cables can be fixed at the outside of the tube with adhesive tape during lowering, where four individual strain sensing cables are installed at each quadrant of the inclinometer tube (see Figure 1, middle). The reliable orientation of the fiber layers can be ensured by the guiding rails of the tube. This setup not only provides redundancy, but also forms the basis for curvature and bending assessment as further discussed in chapter 3.

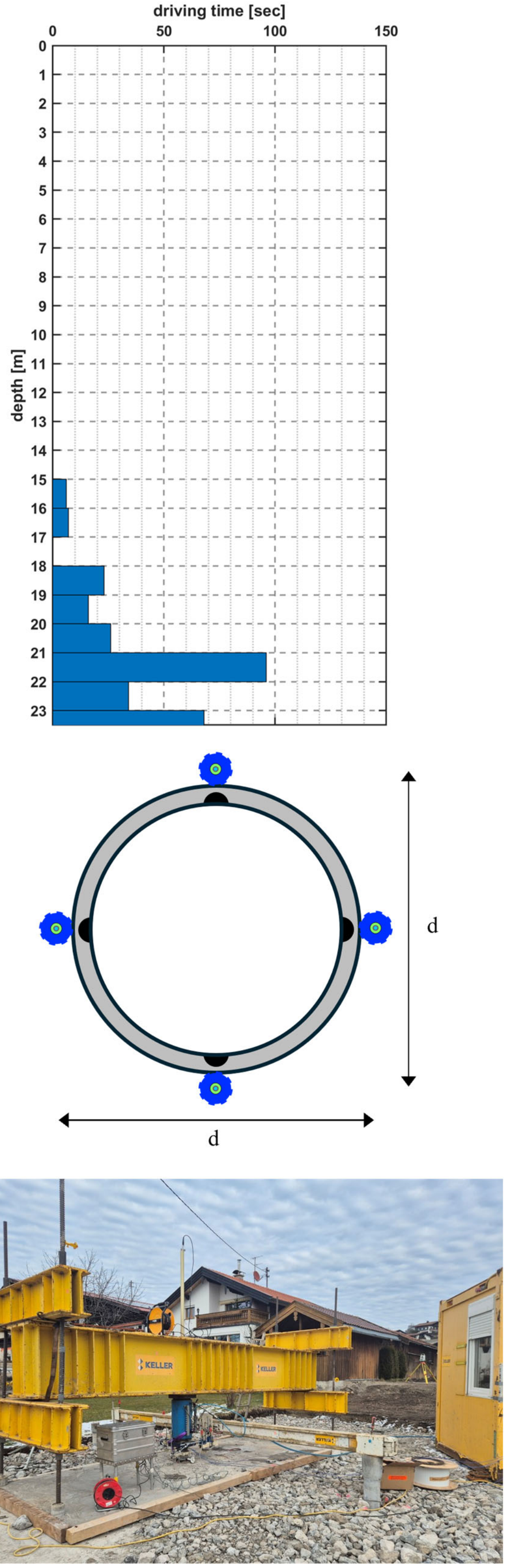

Figure 1. Test Pile Setup: Recorded driving time per meter (top), schematic representation of DFOS arrangement along the pile (middle) and practical realization of test rig (bottom)

The test rig system comprises the test pile itself as well as four reaction piles, covering the counter load from the hydraulic jack. Relative movements in vertical direction are continuously measured during testing using linear variable distance transducers (LVDT) at the test pile head. In addition, numerous geodetic prism targets are mounted at the test pile as well as the reaction piles. Total station (TS) measurements are carried out at each load step to provide the 3D absolute displacements of all individual system test rig parts during testing.

3 CURVATURE & BENDING ANAYLSIS

Strain transducers like fiber optic sensors are widely used in structural monitoring to assess one-dimensional strains ε in the longitudinal axis of the sensor. The measured strain value can be related to the longitudinal stress σ using the modulus of elasticity E:

$$\sigma = E \cdot \varepsilon \tag{1}$$

If two sensors are placed in different distance to the neutral axis of the structure (e.g. at opposite side as shown in Figure 1), the stress behavior varies in case of horizontal bending perpendicular to the sensor direction. It is known from elastic bending theory (see e.g. Megson, 2005) that the deflection w at one specific sensing location x along an object can be described by

$$w(x) = \iint \frac{M(x)}{E \cdot I_y}\, dx^2 = \iint \kappa(x)\, dx^2 \tag{2}$$

where M is the bending moment and I_y the moment of inertia at the observed position. The deflection w can also be expressed by the local curvature value κ and, therefore, by the bending radius R. At this point, the relation between the bending radius and the measured strains ε_1 and ε_2 along the different layers in combination with the distance between the sensors d can be used to directly assess the curvature characteristics at position x:

$$\kappa(x) = \frac{1}{R(x)} = \frac{\varepsilon_1(x) - \varepsilon_2(x)}{d} \tag{3}$$

Uniform stresses in longitudinal direction due to tensile stresses and/or temperature dependent length affect both fiber layers identically and can be taken into account by

$$\kappa(x) = \frac{1}{R(x)} = \frac{\varepsilon_1(x) - \varepsilon_2(x)}{d \cdot (1 + \varepsilon)} \tag{4}$$

where ε represents the mean value of both fiber layers. The DFOS profiles along the all quadrants can now be used to derive the curvature distribution in both main directions of the pile with small, equidistant segments dl equivalent to the spatial resolution of the measurement system. The deflection w at one specific position x along the object can be finally derived by

$$w(x) = \iint \kappa(x)\, dl^2 \tag{5}$$

The boundary value problem of the double integration is solved using the geodetic displacements observed at each load step at the pile head and its vertical orientation into the ground. Moreover, the initial curved state of the pile resulting from the driving process can be taken into account by considering the initial shape captured by the inclinometer measurements before loading. This step is optional, but can further improve the system's accuracy. For further information on the strain-based shape sensing principle and details on the numerical double integration process, reference is given to Monsberger (2022).

4 TESTING RESULTS

Both test piles have been investigated within static compression load tests up, where the load has been step-wise increased based on standardized loading scenarios. The loading process and the horizontal displacements measured by the total station at the pile head of PP02 are shown in Figure 2.

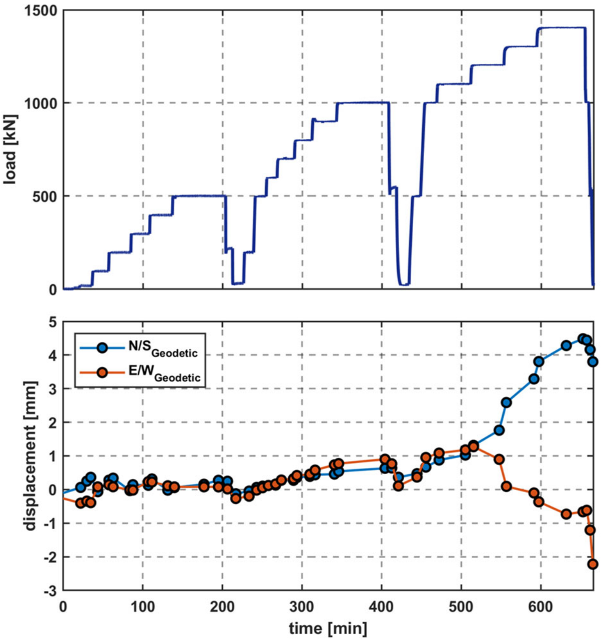

Figure 2. Applied loading (top) and measured geodetic displacements (bottom) during static testing of test pile PP02

It can be seen that there is no direct linear relation between the applied loading force and the horizontal displacement readings. The geodetic readings are mostly constant within 1 mm up to the load step of 1100 kN, which is in the range of the TS's measurement repeatability. Significant horizontal movement only arises at the last three load steps with maximum displacements of up to 4.5 mm. These results confirms that the compressive load is introduced entirely in vertical direction without essential horizontal movement at the pile head.

The installed DFOS system was continuously interrogated during the test to capture the (compressional) strain distribution resulting from the applied loading force. As an example for the distributed measurement results, Figure 3 (left and middle) depicts the strain sensing profiles along pile PP02 for the installed sensing cables at the 600 kN load step. Similar behavior can be observed for all sensors as the introduced load is continuously transferred from the pile to soil with an almost linear decrease of the strain sensing values from the pile head to the bottom point. It can however be noted that slight deviations between the different layers become visible, especially along the first 10 m, which indicate bending in horizontal direction.

The curvature distribution for both sensing direction can be derived from the strain sensing profiles by considering the distance between the DFOS layers of d = approx. 56 mm (cf. Figure 1). The curvature progress shown in Figure 3 (right) corresponds to the general assumption that the bending moment vary at the upper part in the shape of an approximated sinuous line in case of weak soil conditions. This impact is visible for both sensing directions, but shows more significant influence expect for the area next to the pile head for the North-South direction, where curvature variations can be recognized up to a depth of approx. 13 m.

In order to analyze this effect in an appropriate manner, the DFOS curvature values can be numerically double-integrated to obtain the fully-distributed bending behavior along the pile. Each double-integration is supported by the geodetic displacement readings at the pile to solve the arising boundary value problem. The displacement profiles for selected load steps along pile PP02 are shown in Figure 4 (left), where the resulting shape indicates bending with increasing loads. As expected, the pile alternately swerves at the top part before it linearly evades starting from a depth of about 13 m. Even if this behavior seems reasonable, the displacement magnitude is quite small with a maximum deflection of approx. 15 mm at the highest load step of 1400 kN. Moreover, it must be noted that the deflections do not constantly increase with increasing load

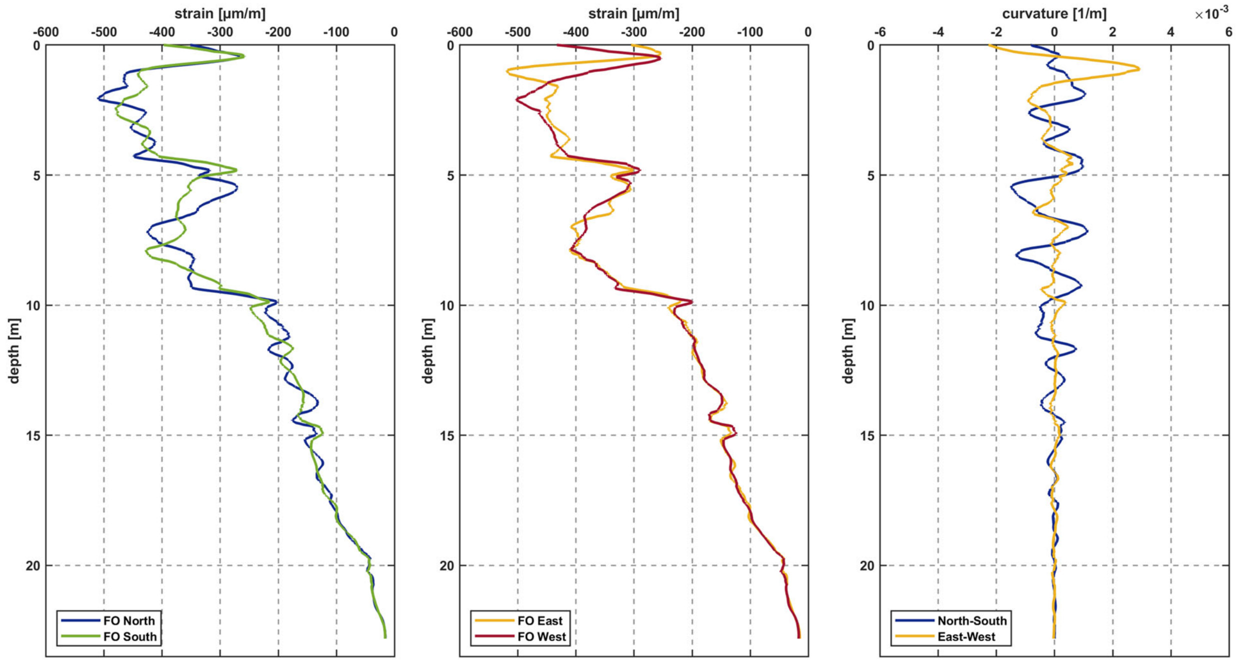

Figure 3. DFOS strain profiles measured along test pile PP02 at 600 kN along the North-South direction (left), East-West direction (middle) and derived curvature distribution for both directions (right)

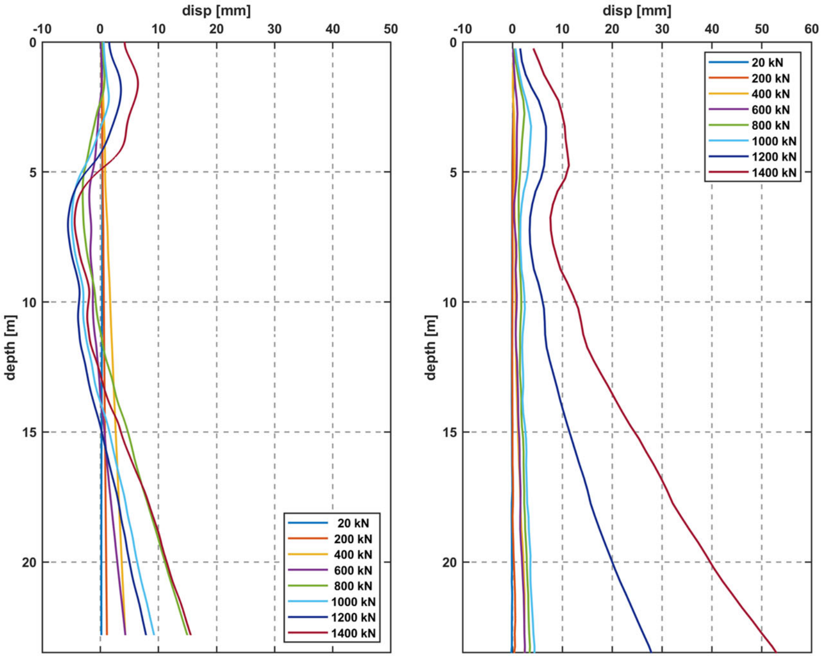

Figure 4. Bending profiles along test pile PP02 (North-South direction) for different load steps derived from DFOS strains (left) and inclinometer measurements (right)

and occasional outliers, e.g. 800 kN, can be identified. The derivation methodology is based on the double integration of the measured strain values and hence, erroneous data of single points affects not only their location, but also the entire bending derivation significantly. The resulting bending curves must be therefore analyzed with respect to the strain profiles to identify and eliminate potential fault zones.

Additionally to the DFOS system, inclinometer measurements were performed along the installed tube at each load step. Unlike traditional evaluations, where the bottom point is assumed to be stable, the displacement curves presented in Figure 4 (right) are fixed to the geodetic readings at the pile head, which allows an appropriate comparison directly to the DFOS derivations. Both technologies depict a similar shape with deviations in the orientation. The inclinometer measurements do not indicate essential bending before the 1200 kN load step. Furthermore, their absolute value is significantly higher with maximum deflections at the highest load step of more than 50 mm. This behavior is doubtful as the end-bearing pile shall not able to deflect essentially in horizontal direction.

5 CONCLUSIONS & OUTLOOK

This paper has reported about an innovative distributed fiber optic monitoring approach to monitor shape characteristics along driven ductile piles. The test site faces challenging conditions with low-bearing lacustrine clay and silt situated with minimal shaft friction along the pile's upper part, which is why buckling effects are likely to occur, especially for small pile diameters.

It is state of the art to utilize DFOS to monitor strain profiles during compression tests and to derive the resulting shaft friction distribution along the pile (see e.g. Pelecanos et al. 2018). The presented DFOS setup however utilizes four individual sensing cables in each quadrant of the pile, enabling enhanced curvature and bending analysis perpendicular to the sensor installation. The testing results demonstrate that the system is capable to provide fully-distributed bending profiles along the pile and therefore, to assess arising buckling without accessing the test rig after installation. The DFOS results can be analyzed in conjunction with geodetic displacement readings at the pile head and compared to internal inclinometer measurements along the pile. The different technologies show decent agreement with similar shapes, but deviations in the orientation and absolute displacement magnitude. Appropriate laboratory test setups could here provide a more detailed understanding of the DFOS capabilities by analyzing the interaction between the inclinometer tube, the sensing cables and the surrounding concrete material.

6 REFERENCES

Fabris, C., Schwaiger, H.F., Pulko, B., Woschitz, H. and Račanský, V. 2020. Numerical Simulation of a Ground Anchor Pullout Test Monitored with Fiber Optic Sensors. *Journal of Geotechnical and Geoenvironmental Engineering* 147(2), 04020163, 10.1061/(ASCE)GT.1943-5606.0002442.

Hayden, M. 2024. *Pile HAY-Proof-System® Neuartiges System für statische Probebelastungen*. PhD Thesis, Graz University of Technology.

Megson, T.H.G. 2005. *Structural and stress analysis.* 2nd ed., Elsevier Ltd., London, United Kingdom 10.1016/B978-0-7506-6221-5.X5000-0

Moser, F., Lienhart, W., Woschitz, H. and Schuller, H. 2016. Longterm monitoring of reinforced earth structures using distributed fiber optic sensing. *Journal of Civil Structural Health Monitoring* 6, 321–327, 10.1007/s13349-016-0172-9.

Monsberger, C.M. 2022. *Distributed Fiber Optic Shape Sensing in Structural and Geotechnical Engineering: Principles and Applications*. PhD Thesis, Graz University of Technology. Shaker Verlag, 10.2370/9783844088250.

Monsberger, C.M., Lienhart, W. and Hayden, M. 2020. Distributed fiber optic sensing along driven ductile piles: Design, sensor installation and monitoring benefits. *Journal of Civil Structural Health Monitoring* 10, 627–637, 10.1007/s13349-020-00406-3.

Pelecanos, L., Soga, K., Elshafie, M.Z.E.B., de Battista, N., Kechavarzi, C., Gue, C.Y., Ouyang, Y. and Seo, H.J. 2018. Distributed fiber optic sensing of axially loaded bored piles. *Journal of Geotechnical and Geoenvironmental Engineering* 144(3), 1-16, 10.1061/(ASCE)GT.1943-5606.00018 43