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INSTRUMENTED STATIC LOAD TESTS ON FOUNDATION PILES

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ABSTRACT

Static Load Tests (SLTs) on pile foundations are a crucial tool for understanding and optimizing the design of pile foundations. Test piles are often instrumented with strain gauges. The use of optical fibres for this purpose offers significant advantages over traditional strain measurement methods (such as extensometers based on electrical resistance or vibrating wire) in terms of ease of installation, as well as the quantity and quality of data collected.

The optical fibre is made of a fibreglass. Elongation or shortening of the fibre will cause a change in the light transmission in the optical fibre. The acquisition system is able to measure those changes.

At Buildwise, two different technologies are often used; FBG and BOFDA. The FBG type is a discontinuous measurement while the BOFDA type is a continuous one.

Buildwise database of approximately 300 results of SLTs provides the framework for tests conducted as part of the certification of pile systems. The measured load-bearing capacities are compared with the calculated capacities (in Belgium, based on CPTs). The comparison is made not only on the total bearing capacity but also on the shaft and base bearing capacities.

An automatization of the pile calculation, in accordance with the Belgian standard has also been developed. The presentation will elaborate on these various aspects, including the instrumentation of piles with optical fibres, the execution of load tests, the development of a robust database, and the standardization of calculation methods for pile system certification.

Keywords: pile foundation, Static load test (SLT), optical fibre, database.

INTRODUCTION

Pile foundations are essential in civil engineering to transfer structural loads to deeper, stable soil layers. Static Load Tests (SLTs) are widely used to verify design assumptions and enhance predictive models. Traditionally, SLTs employed strain measurements from electrical resistance or vibrating wire sensors. The introduction of optical fibre technologies has improved installation simplicity, data resolution, and robustness, enabling precise characterization of load transfer along the pile. Buildwise has compiled over 300 SLTs, comparing measured capacities with theoretical predictions from Cone Penetration Tests (CPTs), contributing to the validation of national design standards. This paper presents the instrumentation techniques, testing procedures, database insights, and the automated calculation of pile capacities according to Belgian standards.

OPTICAL FIBRE TECHNOLOGIES

Buildwise has used optical fibre technologies in SLTs for over 15 years. The main systems are Fibre Bragg Grating (FBG) sensors, which provide discrete strain measurements along the pile by reflecting light at wavelength shifts proportional to strain (https://ovmonitoring.be/). Up to 20-30 FBG sensors can be multiplexed on a single fibre, with spacing adaptable to the pile length. A major advantage of FBG is its capability for high-frequency data acquisition (up to 5 kHz), enabling dynamic monitoring during pile driving or load testing if required.

As shown in Figure 1a, up to 20 to 30 FBG sensors can be multiplexed on a single fibre cable, with each sensor designed to reflect light at a distinct wavelength. This multiplexing is configured during manufacturing, depending on the desired sensor spacing and the available spectral range. To prevent overlap or “peak swapping” between neighbouring sensors, sufficient spectral separation must be maintained, which inherently limits the total number of sensors per fibre.

In parallel, Brillouin Optical Frequency-Domain Analysis (BOFDA, see Figure 1b) offers distributed strain and temperature monitoring by treating the entire fibre as a sensor. BOFDA provides continuous profiles with a spatial resolution of about 0.20 m but is limited to static or quasi-static measurements due to its slower acquisition rate (3-5 minutes per scan) (https://ovmonitoring.be/).

More recently, Buildwise has adopted Rayleigh-based sensing, which provides high spatial

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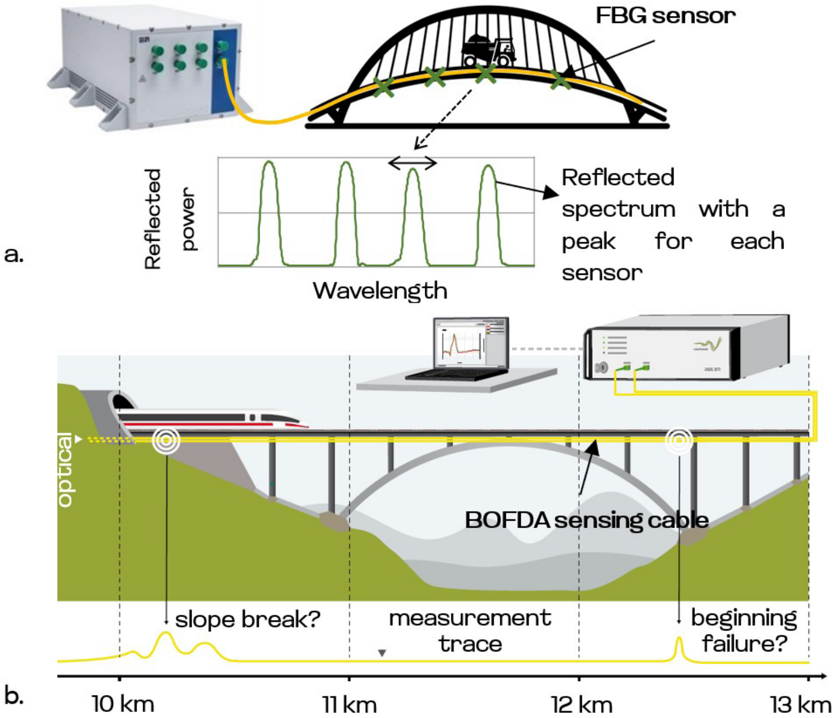

Figure 1 *Schematic overview of the principle of (a) the FBG technology and (b) the BOFDA technology (based on an illustration from fibrisTerre)*

resolution (millimetre scale) using standard optical fibres and faster acquisition (up to 250 Hz).

PILE DESIGN IN BELGIUM

In Belgium, pile design follows the Dimensioning Method 20 (Méthode de dimensionnement n°20, 2020), referenced by the National Annex of Eurocode 7. The ultimate bearing resistance is calculated as the sum of the base and shaft resistances:

$$R_c = R_b + R_s \quad (1)$$

The base resistance Rb is defined as:

$$R_b = \alpha_b \varepsilon_b \beta \lambda A_b q_b \quad (2)$$

and the shaft resistance as:

$$R_s = \chi_s \sum (\alpha_{s,i} \alpha_{D,i} h_i q_{s,i}) \quad (3)$$

where factors account for soil type, installation technique, and pile geometry, with q_b derived from CPT data following the De Beer method and q_s derived from CPT data and the Dimensioning Method 20. The Dimensioning Method 20 categorizes soils as either clays or "other soils" (sands, silts, loams, gravels), affecting the selection of installation factors. Certified pile systems benefit from more favourable coefficients, reflecting improved performance and quality assurance.

To streamline calculations and improve consistency, Buildwise developed an automated tool based on the Dimensioning Method 20. It processes CPT data, performs soil classification, and computes base and shaft resistances, interfacing directly with Buildwise SLT database.

ANALYSIS OF INSTRUMENTED SLT RESULTS

The SLTs were performed according to NBN EN ISO 22477-1 (NBN EN ISO 22477-1, 2019), which prescribes a single loading/unloading cycle with constant load increments. Load application is monitored by a calibrated load cell, while pile head displacements are recorded by four displacement transducers mounted on independent reference beams.

Optical fibre sensors are installed via reservation tubes attached to the reinforcement cage or a central steel bar. Fibres are bonded with cement grout prior to testing.

The optical fibre sensing technologies employed—FBG, BOFDA, and Rayleigh-based technologies—all provide strain data in terms of microstrain ($\mu\varepsilon$).

To convert the strain measurements into force, the method developed by Fellenius (Fellenius B.H., 2001) is applied. This method assumes that the stress-strain relationship of concrete under axial loading can be described by a strain-dependent modulus of elasticity, such that:

$$\sigma = a\varepsilon^2 + b\varepsilon \tag{4}$$

Expression (4) can also be expressed with:

$$\frac{d\sigma}{d\varepsilon} = 2a\varepsilon + b \tag{5}$$

For each load step and for each sensor along the pile, the incremental ratio ΔQ/Δε is calculated, where ΔQ is the increase of the applied load at the pile head per step and Δε is the corresponding measured increase in strain at the sensor location.

As the applied load is gradually increased, axial load is transferred downward through shaft friction along the pile. At each depth, as long as shaft resistance above a sensor is not yet fully mobilized, a portion of the applied load is transferred in the overlying soil layers. In this condition, ΔQ/Δε at the sensor remains less than the full material stiffness $E_{tg}(\varepsilon)$ A, where A is the cross-sectional area of the pile and $E_{tg}(\varepsilon)$=2aε+b is the tangent Young's modulus at the measured strain.

Once all shaft friction above a given sensor is mobilized, the measured ratio ΔQ/Δε converges toward the local material stiffness, i.e.:

$$\frac{\Delta Q}{\Delta \varepsilon} = \frac{\Delta F}{\Delta \varepsilon} = E_{tg}(\varepsilon) \cdot A \tag{6}$$

where F is the increase of load at the location of the sensor.

A linear regression provides the secant modulus and axial force distribution:

$$\frac{\Delta F}{\Delta \varepsilon} = (2a\varepsilon + b) \cdot A \tag{7}$$

$$\rightarrow F = \left(a\varepsilon^2 + b\varepsilon\right) \cdot A \tag{8}$$

Once the axial force distribution along the pile has been derived from strain measurements (see Figure 2), the unit shaft friction can be deduced by relating force reductions to soil layering from CPT data. Layer-specific friction values can then be compared to design values from the Dimensioning Method 20.

In cases where the SLT is stopped before failure, the Chin method (Verleysen P., 1993) is used to extrapolate the ultimate load, assuming a hyperbolic load-settlement trend:

$$\frac{s}{Q} = Ms + B \tag{9}$$

$$\rightarrow \quad Q = \frac{s}{Ms + B} \tag{10}$$

This method has proven reliable for estimating ultimate capacities when sufficient settlement data is available, even without full geotechnical failure.

OVERVIEW OF BUILDWISE DATABASE

Buildwise has developed a comprehensive database of SLTs to support both applied research and the certification of pile foundation systems. To date, approximately 300 SLT results have been compiled. Among these, about 200 tests have been instrumented. Although the majority of tests were performed under axial compression loading, the database also includes tension and lateral loading configurations.

Each entry contains standardized information: pile type (according to the Dimensioning Method 20), soil conditions, pile geometry, and load-settlement data at both pile head and base. For instrumented piles, the distribution of shaft and base resistance is derived from strain measurements. When geotechnical failure is not reached, ultimate resistances (total, shaft, and base) are extrapolated to enable comparisons.

The database systematically links test results with nearby CPTs, storing key parameters such as cone resistance, friction ratio, and calculated bearing capacities according to the Dimensioning Method 20. This structure enables direct comparison between measured and calculated capacities.

Analyses include load-settlement curves, load distribution profiles, and normalized resistance plots, facilitating evaluation of load transfer mechanisms and design conservativeness. Normalizing settlement by pile diameter allows meaningful comparisons across different pile sizes and geometries.

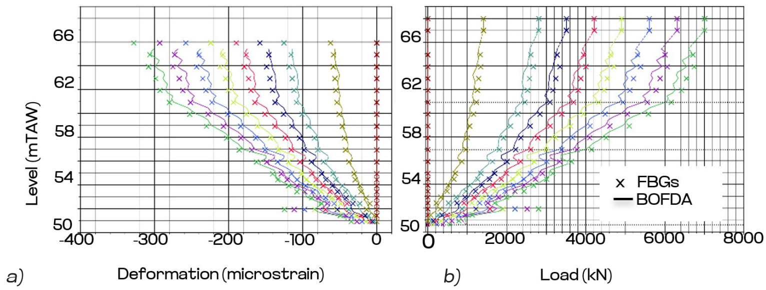

Figure 2 *(a) Distributed strain and (b) load profile along pile depth for the different loading steps during a static load test*

For broader insights, tests can be grouped by pile type and soil conditions. Figure 3 exemplifies such a grouping, showing measured-to-calculated total resistance ratios against normalized base settlement for displacement screw piles in "other soils." This helps assess the reliability of design assumptions under consistent conditions.

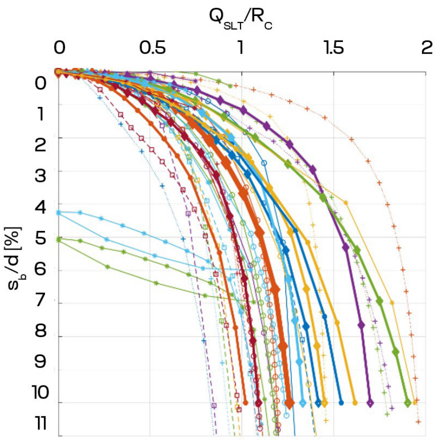

Figure 3 *Measured-to-calculated ratio Q_c/R_c versus normalized settlement s_b/D_b for piles of the same type in similar soil conditions*

Overall, the database forms a robust basis for validating theoretical models, refining design parameters, and supporting technical certification, promoting a data-driven approach to foundation engineering.

CONCLUSION

The use of optical fibre technologies in static load testing has significantly enhanced the ability to characterize load transfer mechanisms along pile shafts and at the base, offering higher resolution, reliability, and adaptability than traditional measurement techniques. By integrating these measurements within a structured methodological framework, Buildwise has contributed to the development and application of standardized procedures for pile design through the elaboration of the Dimensioning Method 20 and active involvement in the pile certification process in Belgium. The development of an automated design tool aligned with the Dimensioning Method 20 further strengthens the link between theoretical predictions and field performance. The Buildwise database, currently comprising approximately 300 static load tests—of which a substantial portion are instrumented—forms the cornerstone of this effort. This database not only supports technical certification but also serves as a platform for ongoing research into pile behaviour across various soil conditions and installation methods.

To enhance the predictive power of the database, new SLT results are continuously integrated. Looking ahead, Buildwise plans to enrich this resource by incorporating pile installation data, including parameters such as drilling torque, speed, pressure, and concreting metrics. This additional layer of information will allow for a more comprehensive understanding of how installation processes influence pile performance, particularly for pile types sensitive to execution methods.

Together, these developments support a data-driven, reliable, and adaptive foundation engineering practice—one in which theoretical models and field evidence are tightly interwoven to ensure safe and optimized geotechnical design.

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