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Application of Distributed Optical Fibre Sensor for Strain and Temperature Monitoring within Continuous Flight Auger Columns

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Abstract. Distributed optical fibre technology provides new possibilities in structural health monitoring in comparison with traditional spot measurements, because it allows to measure selected physical quantities continuously over structural member length. The spatial resolution can start from as fine as 5 mm when using advanced optical reflectometers based on the principle of Rayleigh scattering. The quality of information obtained about structural condition is especially important for geotechnical applications because there are many uncertainties regarding the theoretical model describing cooperation between the foundations and the substrate as well as including the values of physical parameters. Moreover, the geometry of structural members (e.g. the diameter of the column) can be very different from design assumptions and vary along the depth depending on technology of execution. In presented case study the analysis of continuous flight auger (CFA) column was described based on the strain and temperature measurements carried out continuously over the length of 12 m. The measurements were done during the load tests, but also in the early-age concrete, when thermal-shrinkage strains appeared. The way of installation and exemplary results were presented as well as data interpretation was described and discussed hereafter.

1. Introduction

1.1. Continuous Flight Auger Columns

Continuous Flight Auger (CFA) columns are one of the most widely used ground improvement type because of their versatility, simplicity and efficiency. CFA concrete columns are formed by drilling the hollow using special auger to the required depth which is equal to the full design length of the column. The auger construction is essential for this technology – see figure 1. In its central part there is an inner tube, which is closed during driving and opened during extraction from the hole, allowing for down-up concreting in continuously way. At the same time the auger is extracted at a controlled rate, removing the soil to the ground level. Moreover, the auger pushes the soil sideways during penetration causing its partial compaction.

Figure 1. Exemplary execution of Continuous Flight Auger columns on site [Menard archives]

For concreting, the special concrete mix should be used with appropriate consistency and aggregate which allow for tightly filling the space below the auger. The speed of extraction of the auger and a fresh concrete mix pumped under pressure support the stability of the hole during execution. CFA concrete column parameters such as length, concrete consumption, performance duration are automatically registered and should be controlled by the operator.

CFA columns are suited to different kind of grounds. This technology works very well in non-cohesive soils (compacted sands) as well as cohesive soils (semi-solid clay). The main areas where CFA method is used are residential or industrial buildings and bridges which transfer the whole gravity load on the floor, hydraulic structures or other large-format and engineering facilities e.g. road or railway embankments [1]. Depending on the corresponding loads, the following parameters for CFA columns could be selected: diameter (from 0.3 m to 1.2 m), length (up to 30 m) and spacing (usually in the range from 1.2 m to 3.5 m, using rectangular or triangular arrangement).

The widespread use of this technology contributed to widening experiences and knowledge, both among the contractors and designers. As a result of many applications, construction techniques, appropriate material parameters, design algorithms, static capacity evaluations, construction guidelines and quality control techniques were widely discussed and described [2]. Nowadays there are many advanced tools available for theoretical analysis, so there is a possibility to evaluate effective spatial numerical models for designing and optimizing process. For example, CFA column can be modelled as beam element embedded into the continuum through Mohr-Coulomb interface [3] or by connecting different non-compatible meshes using kinematic constraints or a robust mesh tying method [4]. Usually the creation of FEM model is based on the results from in situ investigations such us extended CPT tests, which provide information about the soil layers stiffness. Despite this, it should be emphasized that theoretical considerations including even advanced mathematical models, especially with respect to the heterogeneous concrete and the ground, could lead to the significant errors [5] and always remain imperfect. Thus, appropriate in situ control should be provided to enlarge the practical knowledge, calibrate numerical models and reduce uncertainties within specific case study, minimizing the risk of damage or failure or optimizing the design process.

1.2. Monitoring of concrete columns

Construction process of CFA columns is always monitored by an electronic system, but structural integrity of the columns is still affected by different factors such as concrete quality (low workability), cement consumptions, aggregate segregation or exudation. What is more, installation in difficult soils can lead to structural damages [6], such as cross sections reductions or bulge formations (soft soils), soil mining problems (loose sands with high water level), hole stability and auger rates control problems (ground with voids or water pockets). Moreover, the concrete elasticity modulus as well as the diameter of the column can be very different from design assumptions and vary along the depth.

All this uncertainties and construction difficulties causes that not all CFA columns are free from damage occurrences, which is also confirmed by in situ investigations. In paper [7] the results from representative number of integrity tests were presented and discussed, showing that almost 20% of executions were with considerable quality deficiencies – see figure 2.

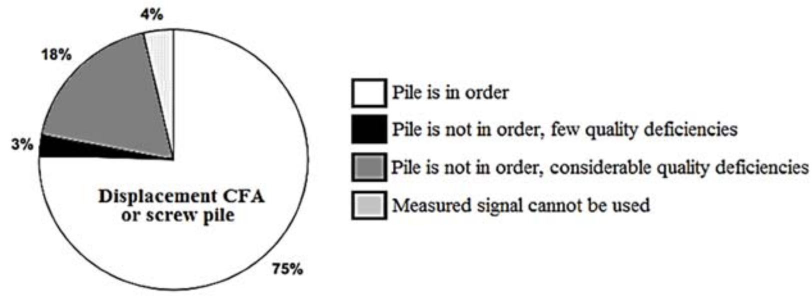

Figure 2. Failure class distribution for CFA or screw piles [7]

These data indicate the necessity of in-situ monitoring, which always should be designed, implemented and evaluated in connection with the geotechnical design [8], what is in line with observational method. There are some standards describing selected tools which can be used for this purpose such as extensometers [9] or inclinometers [10].

One of the most important and challenging task is to evaluate the force distribution along the whole column length, which allow for estimation the load bearing capacity of the column base and its shaft. Such attempts are a common practice in many countries for years [11, 12, 13]. In practice, even the simplest control of pile head displacement is difficult for *in situ* conditions [14], where the stability of reference system is difficult to establish. In Poland, some solution involving vibrating wire sensor technology was recently elaborated and implemented [15]. Another important measuring challenge is to access the load distribution between the ground and concrete columns over a long period of time [16], especially in the case of “energy” piles, serving as heat exchangers.

The main limitation of almost all measuring techniques used in geotechnical instrumentation [17] is that they are based on spot sensors, which returns through measurement only one value of considered physical quantity. Thus, the question about what is happening between measuring points always remains without precise answer. However, nowadays there are the possibilities of applying new measuring tools, including distributed optical fibre sensor technology [18], which provide comprehensive and much more useful information in comparison with traditional techniques. This tools with reference to a specific application within CFA columns are presented and discussed hereafter.

1.3. Distributed optical fibre measurements

Traditional extensometers and many other measuring techniques are able to carry out measurements of a given physical quantity (e.g. strains) only at a local scale - figure 3a. Sometimes attempts are made to analyse distribution of this quantity along a given line by installing several sensors within this line – figure 3b. Distributed optical fibre technology is based on light scattering and allows for strain and/or temperature measurements to be made with a spatial resolution starting from as fine as 5 mm along the length of the optical fibre [19]. From geotechnical point of view, such measurements can be considered as continuous measurements in a geometric sense (figure 3c).

A number of studies on distributed optical fibre measurements have been conducted under laboratory conditions over the last few years. There were attempts to embed measuring fibres into a concrete [20], localize cracks within concrete structural members [21] and analyse their strain and temperature distributions [22, 23] using different optical phenomena such us Brillouin or Rayleigh scattering [24]. What is more, many pilot installations have been carried out in *in situ* conditions in relation to geotechnical structures [25, 26], including different types of piles and columns [27, 28].

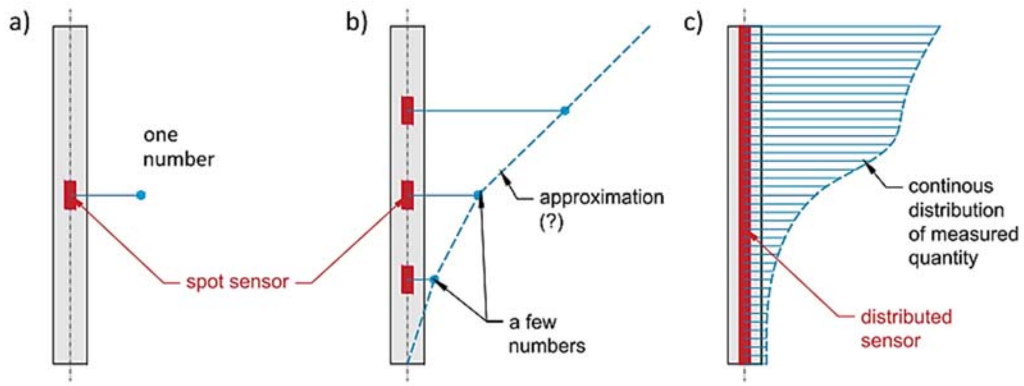

Figure 3. Measurement schemes for concrete columns: a) spot, b) quasi-continuous, c) distributed (geometrically continuous)

In the case study presented and discussed hereafter, the strain and temperature measurements were conducted using reflectometer based on Rayleigh scattering phenomenon [29]. The principle of its operation lies in light scattering in optical fibre caused by the particle structure of matter (heterogeneity of refractive index at micro-scale). The light reflected from the imperfections of the glass fibre moves backward relative to the original direction of motion. Scattering amplitude is a random but constant property for a given fibre and can be analysed by advanced reflectometers which finally converse it for mechanical or thermal strains in reference to zero readings. During the research presented in the following sections of the paper an optical backscatter reflectometer OBR 4600 [30] manufactured by Luna Innovations was applied for distributed measurements. The selected technical parameters of this device are summarised in Table 1.

Table 1. Selected parameters of distributed measurements

Parameter	Value	Unit
Measuring range (standard mode)	70	m
Minimal spatial resolution	5	mm
Temperature resolution	± 0,1	°C
Strain resolution	± 1,0	με

2. Installation of measuring fibres

Two main goals were defined before the installation of optical fibres into the concrete CFA columns:
- to provide appropriate adhesion between analysed medium (concrete) and measuring fibre, which enable adequate and reliable strain transfer;
- to install linear optical fibre sensors to the level as deep as possible without any damages.

These goals were realized through the application of specially designed composite rods integrated with optical fibres, which have been finally braided with polypropylene fibre in two directions and coated with two-component epoxy. This braid, analogously to traditional reinforcing bar ribs, provides mechanical cooperation between concert medium and the sensor. What is more, this solution secures the measuring fibre during installation process (pure glass optical fibre with the coating dimeter of Φ = 250μm would definitely rupture during concreting).

For installation the composite rod with rectangular cross section was selected and optical fibres were glued to its all four surfaces. Knowing the exact distance between the upper and lower fibre (analogously between the left and right) it is possible to converse measured strains into displacements (3D shape). Also, one optical fibre was placed freely into polyamide tube, so it was isolated from mechanical strains and thus used as temperature compensating fibre. Simplified cross section through the optical fibre linear sensor is presented in figure 4.

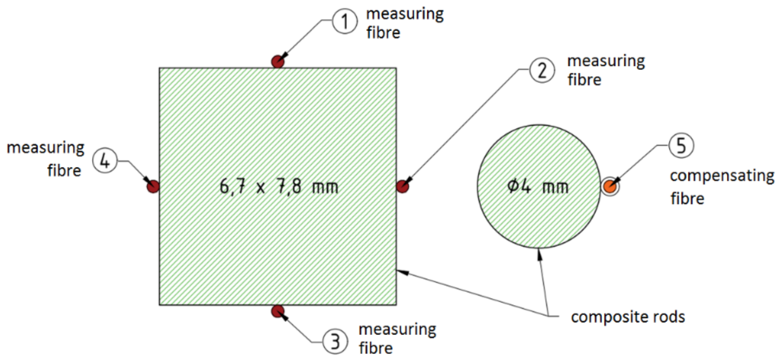

Figure 4. Cross section through the optical fibre sensor

The use of appropriately selected composite material for the sensor core makes installation easier because of its lightness as well as do not disturb the operation of structural member as its elasticity modulus is similar to the concrete modulus.

Figure 5. The view of optical sensor in steel, protecting tube during installation process

Because in the analysed CFA columns no reinforcement was applied, the special procedure of mounting had to be elaborated. Due to the technology requirements optical sensors protected by steel tubes were deepened immediately after concreting. The tube was equipped with special wings to provide its appropriate positioning within the cross sectional area of the column. At the very bottom of the tube the steel cone-shaped element was used to minimalize friction during deepening and also to anchor the sensor within the base of the column. The final step of installation was to remove the tube from the column, were only composite rod with optical fibres stayed with axial position. Some exemplary pictures from installation time are presented in figure 5.

3. Exemplary results

3.1. Early-age concrete strains

One of the main advantage of installation internal optical fibre sensors is the possibility of measuring early-age concrete strains and temperature development. In research described in this article measurements were performed according to a planned schedule and the zero readings were taken immediately after installation.

In the first days of hardening, concrete reduced its volume (the length of the column was shorter and shorter) due to the phenomenon of thermal contraction as well as autogenous and drying shrinkage. But, because the structural member under consideration is not totally free element (constraints through the friction within the shaft), tensile stress could be induced in the material. Depending on the level of constraints as well as the parameters of concrete mix used, this phenomenon can lead to the cracks appearance. This is especially visible in the elements with reinforcement, which is in fact additional internal constraint for the concrete [31, 32]. Thus, applying linear optical fibre sensor for early-concrete strain and temperature measurements within the whole column length is very useful tool which allows for advanced structural condition assessment. With comparison with geological profiles it is also possible to analyse cooperation of the column concrete with surrounding ground at selected depths.

3.2. Mechanical strains during load test

The main purpose of the optical measuring system installation was, however, performing measurements of mechanical strains during CFA column load tests. This test was conducted by applying force to the column head through hydraulic jacket resisted on the steel structure anchored to the four surrounding columns. The view from the site during load test is shown in figure 6.

Figure 6. The view of CFA in situ load tests

The measurements were performed automatically on 5 measuring optical channels with the frequency of 5 minutes. Later, these measurements were compared with data from testing machine, which had synchronized time with optical backscatter reflectometer used for strain and temperature records. The spatial resolution for this calculated physical quantities can be set in post processing starting from as fine as 5 mm – so, from engineering point of view, almost continuously in a geometrical sense (distributed measurements). For this specific case study, the resolution of 10 mm was defined. During load test temperature within the column was practically constant, so it will not be presented further.

In figure 7a selected strain distributions are presented along the column depth, corresponding to the different values of applied force during load tests. We can clearly observe some local extremes within the compression side, which are located in the weakest places in the column. This phenomenon can be caused by reduction of the cross sectional area (A) or the value of concrete elasticity modulus (E) – in general, reduction of the column stiffness EA. Also, the kind of the ground in this areas should be taken into account. Analysis of such local phenomena would not be possible with traditional, spot measurements.

Based on strain distributions and knowing measuring base of the one virtual optical sensor, it is possible to calculate cumulated changes in length (in this case shortenings) of the column – which are presented in figure 7b. For this specific column, summation was started from the depth of 7,5m, but the longest sensor which successfully was installed during this project, was 12m long. This plot has more intuitive engineering interpretation, as it is expressed in mm. The areas were the plot is the most inclined correspond to the local extremes of strains (figure 7a) and physically mean the biggest change in the concrete column length. This data could be effectively used for verification and calibration numerical model of CFA columns cooperated with the surrounding, layered substrate.

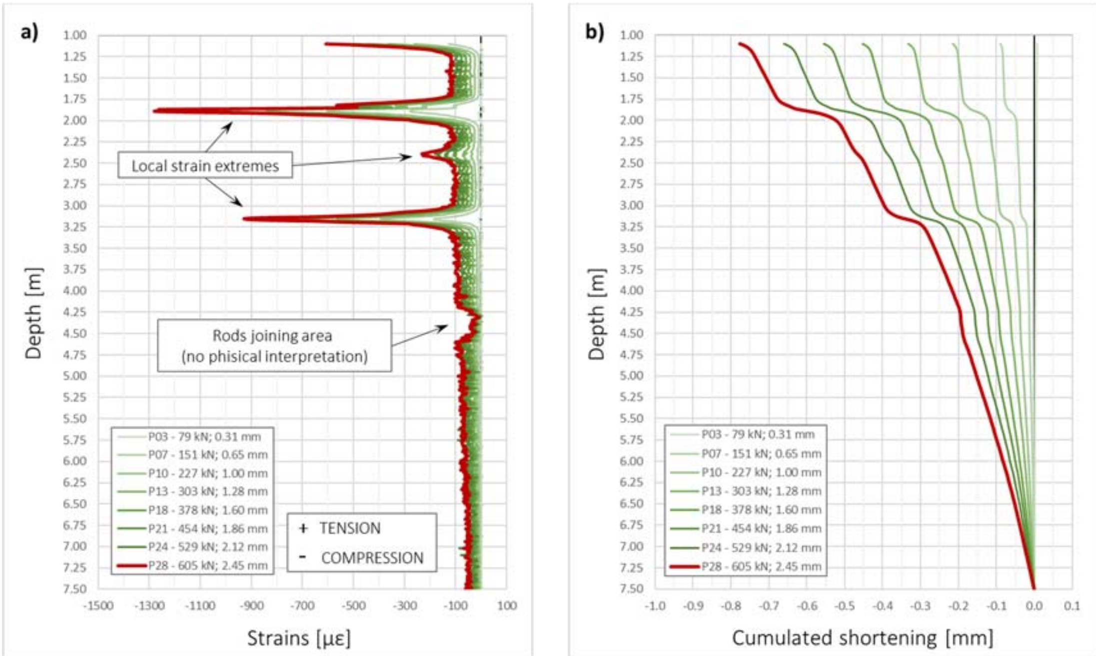

Figure 7. a) Strain [με] distributions within the column depth during subsequent load steps; b) cumulated shortenings [mm] along the column depth during subsequent load steps

Having continuous strain distribution along the whole measuring length, we can choose some depths and define any measuring base (which will be used for strain averaging) to show the strain changes in the function of time. It was done and presented in figure 8 for 6 selected depths and measuring base of 10mm. Now we can clearly observe the course of the load test (consisted of two loading-unloading cycles). We can also see the natural relationship between the depth and the values of strains: the deeper the section is analysed, the smaller changes in strains.

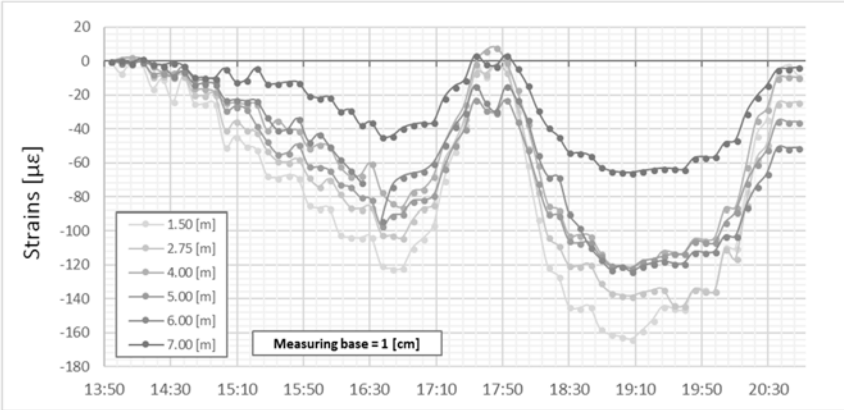

Figure 8. Localization and numbering of measuring fibres within platform cross sectional area

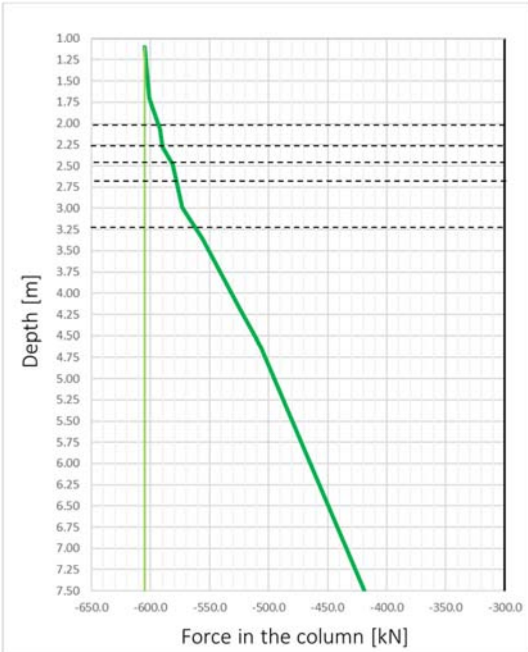

Figure 9. Calculated force values at every depth of measuring line within exemplary CFA column

Based on the measured strains corresponding to the forces applied and recorded by testing machine, as well as making some theoretical assumptions e.g. assuming the constant value of elasticity modulus E and column cross sectional area A, it is possible to estimate the force distribution along the column. In other words, we are able to estimate the part of the force, which is transferred through the shaft to the ground at every depth. Thanks to this analysis, it can be also found whether the column base is involved in force transfer (for such analysis the length of optical sensor has to be equal to the column length). The view of exemplary plot is presented in figure 9. Also other computing techniques are currently being developed in this area.

4. Discussion and conclusions

The pilot researches described in the article include distributed measurements of concrete strains and temperatures within CFA columns. Measurements were performed within the early-aged concrete during its first days of hydration, as well as under mechanical load tests. Analysis of obtained data can be used, among other things, to estimate the integrity and load bearing capacity of the columns, their cooperation with surrounding layered ground as well as to calibrate spatial finite element method model and verify theoretical assumptions. The results are of the crucial importance as other methods based on stress wave transfer in solids (pile or column material) provide acceptable data from the 7th day of concrete setting [33, 34].

Strain, crack and displacement analysis of concrete structural members is crucial in the context of the assessment of their technical condition and safety. This is the reason why works and studies are ongoing to improve the methods used in this field. Based on the research carried out and presented in this article, it can be concluded that the distributed fibre optic technology provides new opportunities in comparison with traditional spot measuring techniques (e.g. inductive, electrical resistance or vibrating wire). Thus, it can and should be used not only for laboratory tests or short-term in situ load tests, but also as a part of long-term structural health monitoring systems, especially in geotechnical applications.

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