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STATIC PILE LOAD TESTS: CONTRIBUTION OF THE MEASUREMENT OF STRAINS BY OPTICAL FIBER

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ABSTRACT: The use of optical fiber for measuring strain and or temperature is increasing in civil engineering. Optical fiber is known to be relatively cheap, compared to the more traditional sensors commonly used, and can, depending on the chosen technology, give a complete distribution along the instrumented element, which can be very interesting in case of an element with variable dimensions along the length of said element. Therefore, for static pile loading tests, the use of optical fiber should present many advantages, compared to more conventional methods of strain measurements. The aim of this paper is to shed new light on the advantages and disadvantages of using optical fiber for the measurement of deformations along a foundation element. After a review of the state of the art of the most commonly used methods, the contribution of the optical fiber for the instrumentation of the foundation elements is evaluated, by comparing the results obtained by the use of the fiber with those obtained with more traditional methods, in some examples of full-scale load tests. Finally, some recommendations are given to maximize the awareness of the potential use of optical fiber in foundation monitoring.

Keywords: Deep Foundations, Piles, Load Test, Instrumentation, Monitoring, Optical Fiber

1. INTRODUCTION

Static pile load test are usually carried either for design purposes, whether it be for control of this design or design by trial, or for constitution of a database then used to elaborate design methods. Therefore, they are critical tests for geotechnical structures and shall be thoroughly prepared.

As such, they are covered by complete and well detailed test standards [1]. Depending on the purpose of the test, the pile may or may not be instrumented. Most instrumentation installed inside piles measures the strain in the pile. Based on the geometry of the pile and the apparent modulus of the material of the pile, force can be derived from strain. Therefore, force-depth diagrams can be drawn for the instrumented piles (Fig. 1).

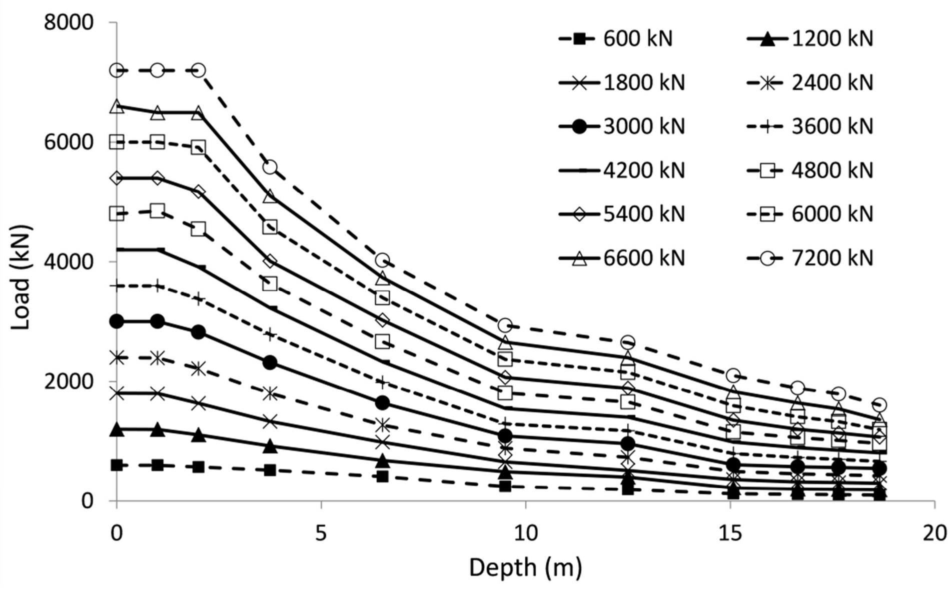

Fig. 1 Force distribution along a Continuous Flight Auger (CFA) pile instrumented with a retrievable extensometer

Shaft resistance and base resistance can then be dissociated, and unit shaft friction can be assessed for each soil layer encountered, depending on the number of measurement points available along the length of the pile. t-z curves, linking the development of the unit shaft friction of a segment of pile to the displacement of this segment, can then be drawn, as well as q_b-z curves. For lateral load tests, the principle is the same, except that it is p-y curves that are determined.

A number of different methods exist for the measurement of these strains, each with its advantages and disadvantages. Among these methods is the optical fiber: since approximately a decade, a number of geotechnical projects have included these technologies for monitoring, including piles [2]-[3]-[4].

This paper aims to first outline the most common methods for the measurement of strains along the shaft of a pile, listing in the process the pros and cons of these methods. Then the use optical fiber for the testing of geotechnical structures, and particularly piles is outlined. The typical difficulties encountered and the benefits of the use of the optical fiber for geotechnical purposes are then highlighted, through practical examples. Conclusions are then drawn, and some innovative uses of optical fiber for the monitoring of foundations are proposed.

2. TRADITIONNAL METHODS FOR THE MEASUREMENT OF STRAINS ALONG A PILE

In this section, the three main methods for the measurement of strains along the shaft of a pile are described in details, and their technical, practical and economical strengths and weaknesses are listed.

2.1 Embedded Strain Gauges

This method is one of the oldest: it consists in placing, at defined depth, strain gauges that will be bonded to the steel cage reinforcing bars (one or more per depth) or pipe.

The advantages of this method are multiple:

- this is a proven technology, with which many practitioners are familiar,
- it is not very intrusive due to the small size of the gauges and the wires, which is a good point for small diameter piles,
- it is quite affordable,
- each sensor is independent from the others, which is important when encountering some damages,
- each sensor can be compensated in temperature.

However, there are a number of disadvantages when using this technology:

- It is time consuming to implement, as there are multiple steps to follow the whole process of preparation and bonding: first, flat rough surfaces should be ground on the rebars, then should be smoothed using finer sandpaper. Surface has then to be cleaned of any impurity using chemical products. The strain gauge may then be bonded to the surface (Fig. 2), using another chemical product, and two layers of protection should then be added on top of the gauge. If the gauges are not pre-cabled, then an extra step will be the soldering of the cables to the gauge. Then, if necessary, soldering should be done for any extra cable length added,
- It necessitates multiple tools and chemical products, some of them having to be kept refrigerated, and a clean environment,
- Wires and gauges are very small, and may be damaged during the process of introducing the reinforcing cage inside the concrete (for CFA piles or equivalent), during the concreting phase (for bored piles), or during the driving phase (driven piles).

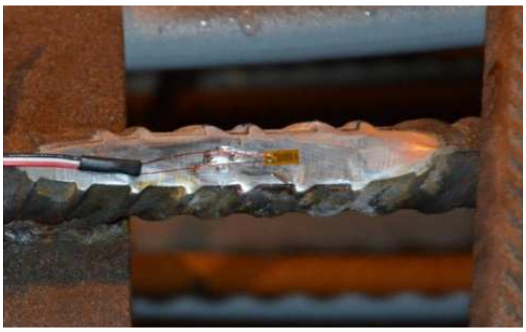

Fig. 2 Naked strain gauge bonded to the rebar

2.2 Embedded Vibrating Wire Strain Gauges

This method is very close to the first one: vibrating wire sensors are attached to the reinforcing bars of the steel cage at different depths, with one or more per depth.

The advantages of this method are as follow:

- the sensors are very robust (made of steel),
- the sensors are not very intrusive (usual length is around 150 mm for a diameter of 25 mm, but can go up to 400 mm in length for particular applications),
- the sensors need only to be attached to the rebars with adhesive rubber tape or plastic zip ties (Fig. 3a),
- the sensors can be bought pre-cabled to the needed length,
- cables are strong enough to resist the

tension during the different phases of manipulation and realization of the piles.
- The sensors are very quick to fix, even if the length of the cables (especially when working on long and / or heavily reinforced piles) can hinder the work and make the intervention longer,
- each sensor is independent from the others,
- each sensor can be compensated in temperature.

On the other hand, this method presents some disadvantages:
- for piles heavily instrumented, the number and thickness of the cables can make this method intrusive, especially for small diameter piles (Fig 3b),
- it can be expensive, when using a great number of sensor and instrumenting long piles, as the cost per sensor and per meter of cable is not negligible.

2.3 Retrievable extensometers

This method is a totally different one. It consists in a chain of sensors that will have to be inserted inside the pile after it realization. Technologies used in retrievable extensometers are usually strain gauges, vibrating wires strain gauges, LVDT or potential sensor based.

The principle is as follows: one or more reservations made of PVC or steel (which can be sonic tube, for example) are cast in the pile. Just before the load test begins, the retrievable extensometer, made of multiple segments whose lengths can vary to adjust to the geology on site, is inserted inside the pipe [5]. When completely inserted and correctly positioned, it is locked into position, using either a pneumatic (with nitrogen being the gas expanding the anchors) or a mechanical system (Fig. 4).

The advantages of this method are as follows:
- it doesn’t need the intervention of a team of external workers during the realization phase,
- the material is not expendable and can be re-used for another pile, which can be economically interesting in case of repeated tests on the same site,
- lengths of segments are adjustable, if needed,
- it is particularly well adapted for the instrumentation of driven piles, as the sensors are not present during the critical phases and therefore cannot suffer from it.

However, this method presents some major disadvantages:
- extra pipes should be positioned inside the reinforcing cage, which require extra work for the contractor before the realization of the pile. These pipes shall also be chosen in relation to the model of extensometer that will be implemented. Particular attention should be paid to the connection/welding of the segments of the pipe, to ensure that nothing obstructs the passage of the extensometer,
- it is intrusive, especially for small diameter piles,
- these extensometers are often limited to 8 to 12 segments, which can sometimes not be enough for long piles in a multi-layers ground,
- nitrogen is needed for the use of most of these systems,
- duration of use is limited in time, as there may be leaks of nitrogen due to worn-out valves and connections,
- it is quite fragile and needs extra care when manipulated,
- spare parts are expensive and not always easily found,
- it needs constant maintenance and highly qualified technicians to maintain it, calibrate it and keep it ready to use,
- on site preparation takes time,
- during on site preparation phase, it necessitates a lot of space to be deployed safely.

All these aspects make the use of a retrievable extensometer expensive, compared to the embedded methods.

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Fig. 3 Vibrating wire strain gauge linked to a rebar (a) and cables exiting the top of the steel cages (b)

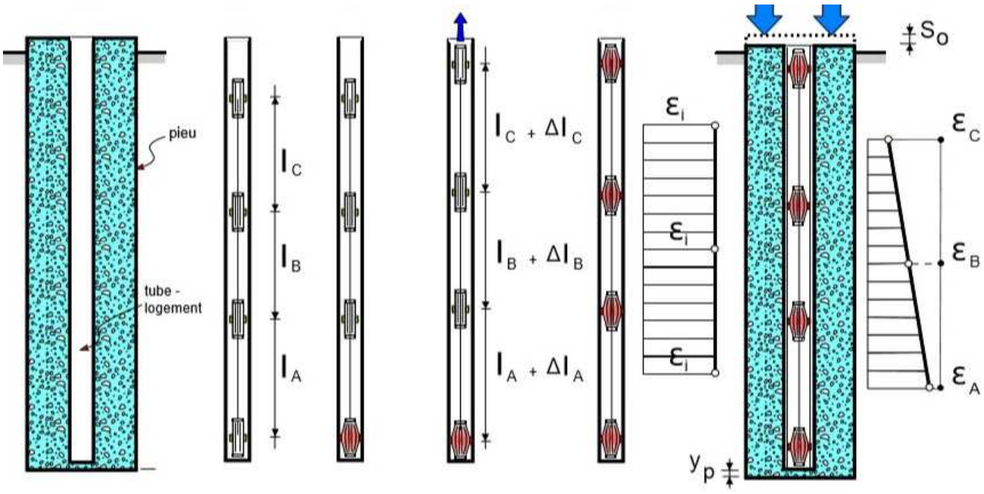

Fig. 4 Operating principle of a retrievable extensometer

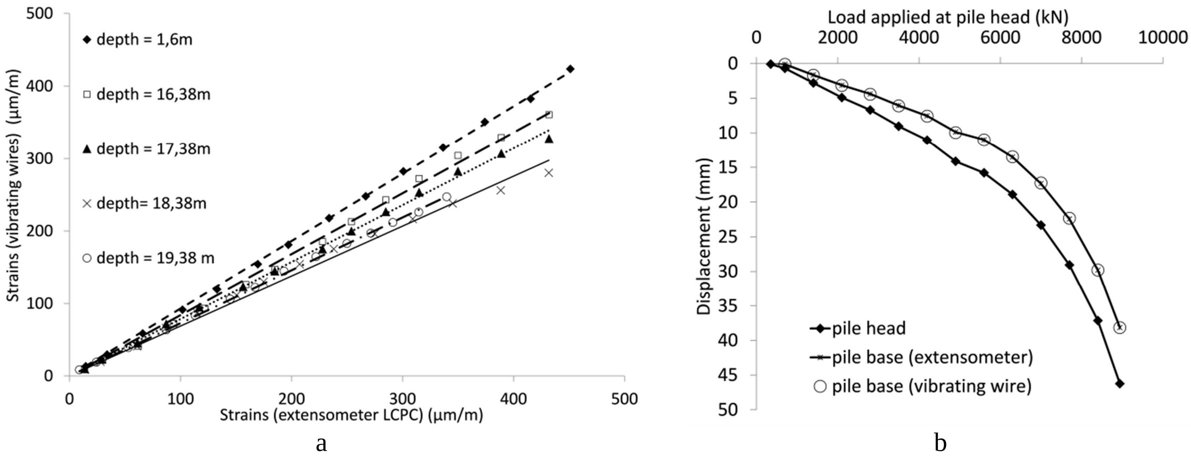

Fig. 5 Comparison of measured strains at different depth (a) and calculated displacements of pile base (b) in a bored pile with a retrievable extensometer and vibrating wire strain gauges

3. EMBEDDED SENSORS VS RETRIEVABLE EXTENSOMETERS

While, for practical and economical reasons, the use of a retrievable extensometer is interesting when testing multiple piles of comparable size and/or driven piles, it becomes less competitive for projects with only a few piles, or with piles with different lengths, for the same reasons.

Furthermore, even if both methods aim is to measure strains along the pile, the measurement may differs : indeed, while the technologies of the sensors used for one or the other are often the same, the principle of measurement differs. The embedded sensors are measuring the strains over a length equal to their own length, while the retrievable extensometers measures strains between two anchors assumed to be fixed, and moving with the pile itself (Fig. 4) [5], making the strain measurement ‘global’ compared to the ‘local’ measurements achieved with embedded sensors.

Therefore, the retrievable extensometers integrate the strains over a longer sample. In consequence these measured strains are often larger than the ones achieved with embedded sensors, with a ratio dependent on the strain level (Fig. 5a). The resulting equivalent moduli derived from these measurements [6] and used to convert strains into loads are in turn smaller.

In addition, the analysis of the results achieved are not as straight-forward as when using embedded sensors, as it is needed to interpolate results at the level of each anchor.

Nevertheless, results achieved with both measuring methods are quite comparable, as can be seen on Fig. 5b for the calculated displacement of the pile base, on Fig. 6a for the load distribution of a given load step and on Fig. 6b for the mobilization of shaft resistance during a static load test [7], and the utilization of one method or the other should therefore be only linked to the context of the project, as it is not a question of accuracy.

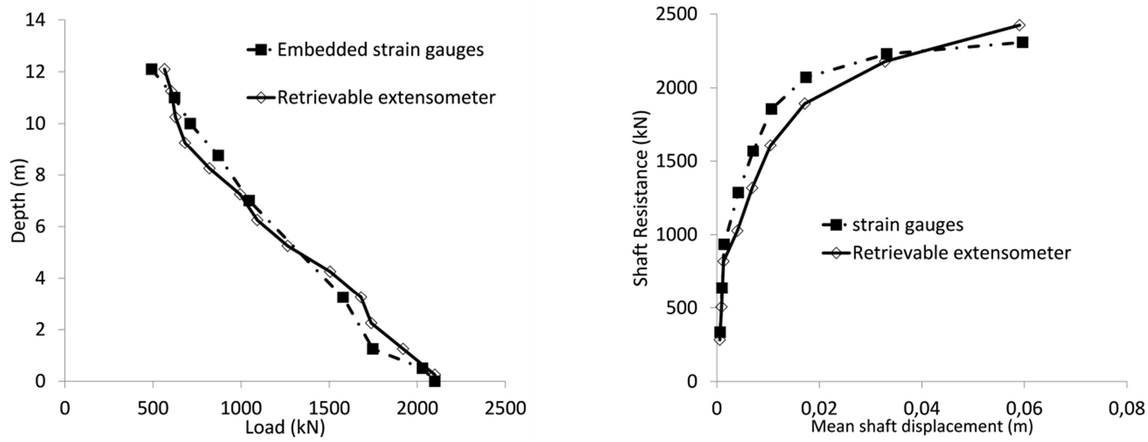

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Fig. 6 Comparison of load distribution for a given load step (a) and shaft resistance mobilization (b) for a CFA pile: results achieved with strain gauges and retrievable extensometer.

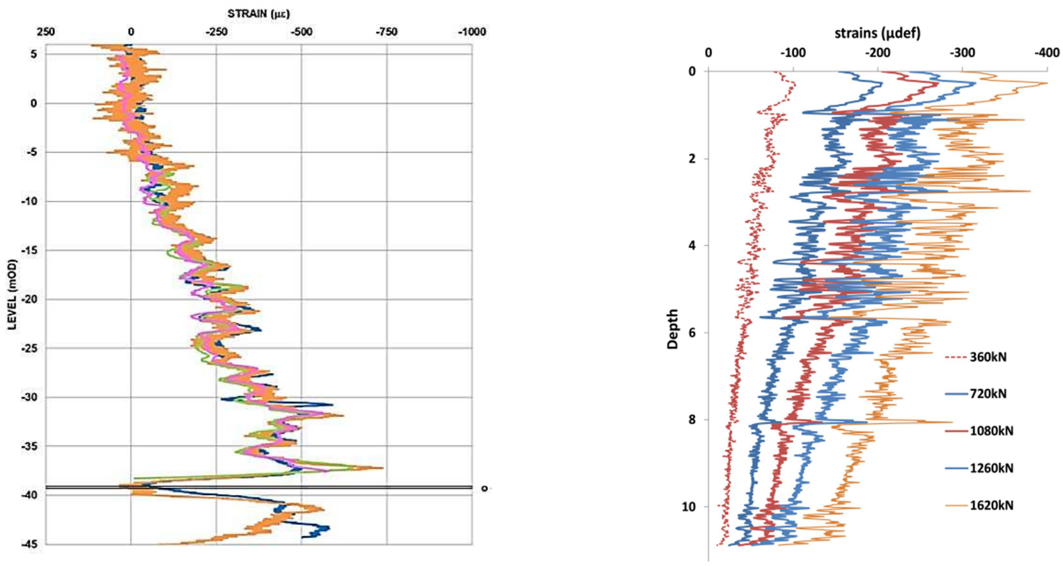

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Fig. 7 Strain distribution for a given load step (a) [2] and for different load steps (b)

4. CONTRIBUTION OF THE MEASURES OF STRAINS BY OPTICAL FIBER

Implementing optical fiber for the measurement of strains in piles was first done when long term monitoring of strains and temperatures was needed : therefore, at first, piles instrumented with these technologies were thermo-active piles.

Nowadays, with positive practical feedbacks on the use of this method available, it can be used for standard piles, for control or development purposes, as it allows measurements all along the fiber, with a resolution up to a few millimeters, depending on the technology used (Fig. 7) [8], and measurements achieved are in excellent concordance with measurements achieved with vibrating wire strain gauges (Fig. 8a).

The use of optical fiber for the measurement of strains presents some advantages:

- implementation, when choosing to simply link the fiber with duct tape to the rebars, can be very quick,
- it is almost non-intrusive, as the fiber is generally only a 3 or 4 mm in diameter,
- it is very appropriate for determining moments and p-y curves, as it provides a very high number of measurements along the pile,
- it can be temperature compensated,
- cost of the fiber in itself is very low and makes it possible to instrument most rebars.

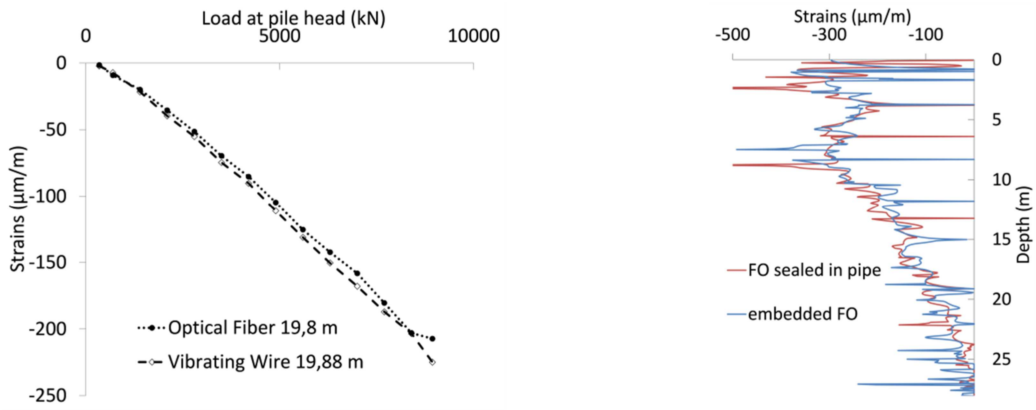

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Fig. 8 Strain measurements comparison between optical fiber and vibrating wires (a) and Strain distribution for a given load step with an embedded fiber and a fiber sealed in pipe (b)

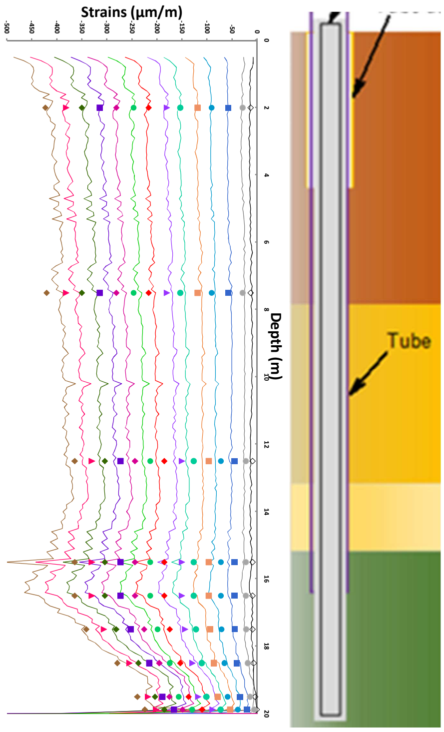

Fig. 9 Strains measures along a bored pile: effect of tubing

Optical fiber can also be inserted inside a pipe if available, and then sealed with grout, allowing for a possibility to monitor a pile if something were to go wrong with the primary instrumentation. Results from such instrumentation can be seen on Fig. 8b, where they are compared to results achieved with a fiber linked to a rebar : measurements are quite comparable and therefore this method can be used if needed. It is interesting to note that strains presented on Fig. 7b were also measured through this method, as the timing of the project did not allow for the pile to be instrumented before being realized.

Furthermore, it also allows to detect layers that where not detected during the geotechnical investigation, and to observe behaviour that would not be seen when using a discrete methods of measuring strains.

Figure 9 shows the strains measured with an optical fiber and vibrating wire strain gauges, on a bored pile tubed down to 16m: at the end of the tube, strains measured by the optical fiber increases, due to a decreased stiffness of the pile, while the strain gauges, which are discretly distributed along the shaft, do not reflect this local behaviour [9].

A variation in diameter is also always possible, when encountering a softer layer for exemple, and a continous measuring method is particularly adapted to detect these occurences [10].

However, it is important to be aware of the difficulties / disadvantages of the optical fiber :

- while the cost of the fiber in itself is very low, the interrogator price is usually very high,
- the interrogators are often not so rugged, and can be damaged during on site monitoring, due to dust presence mostly. Some interrogators are very vibration sensitive,
- the fiber is also very fragile, and must be treated with extra care during set up, especially at the pile base, where the fiber is most exposed during concreting or insertion phases (Fig. 10a), and during construction phases such as lifting, when tensile stress due to the bending of the cage can exceed fiber tensile resistance (Fig. 10b), to avoid any break.
- the fiber acting as a chain of sensors, a broken fiber will result in the total loss of information under the break.

Furthermore, the steps of the realisation of a connection are numerous and tedious. The environment needs to be very clean, with close on site activities as low as possible. The apparatus needed are presented in Fig. 11.

Bad connections result in loss of signal that will in turn result in loss of precision, that will have to be added to the impact of the deployement method of the fiber and the pile.

It is also important to remark that, for cast in place piles, the concreting phase has an important impact on the initial response of the fiber, a seen on Fig. 12, which represent the variation of the frequency, along the length of a the fiber, before loading. The response of the fiber being chaotic, with huge variations in terms of measured strains happening over a very short length, the accuracy of the measures as well as the determined position of any particular point along the pile must be impacted by this concreting phase, depending on the fiber used, as well as the technology chosen and the developed algorithm.

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Fig. 10 Fiber protection at the pile base (a) and cage lifting phase (b)

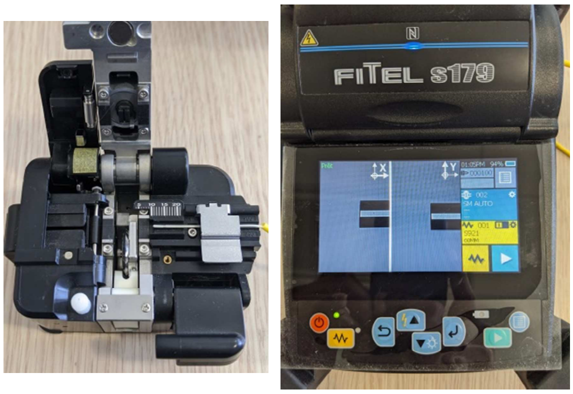

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Fig. 11 Presentation of the different welding stages

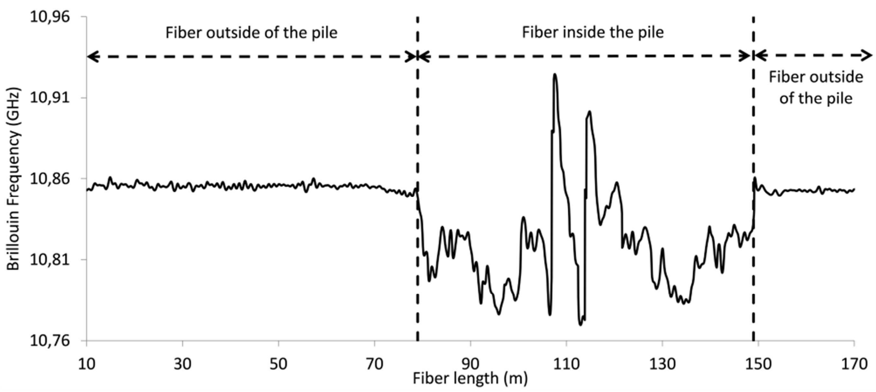

Fig. 12 Brillouin signal of a fiber outside and inside a pile (frequency vs length)

5. CONCLUSIONS

The use of optical fiber for the measurement of strains during pile load tests or other related projects is now a method that is very reliable.

While measured values may differ from values achieved by more conventional technologies, this is only due to differences of measurement methods of the methods. Interpretation of the data shall give the same results as the other methods, whether it be displacements of the pile segment or load distributions along the pile, albeit with a higher resolution.

Nonetheless, it is still very rare to see this technology used for pile monitoring, the two main reasons for this being that:

- the set up, implementation and manipulation of the fiber should be done in a very controlled environment and with extra care, as it is very fragile.
- while the cost of the fiber is relatively low, the price of the interrogator, coupled with its fragility, leads to a certain reluctance to deploy them in dusty environments prone to hazards endangering their integrity and their proper functioning.

It is also important to note that for cast-in place piles, the concreting phase must have an important impact on the fiber in itself, straining and stressing it locally very differently for one point to another. This can have a non-negligible impact on the results, especially if a high resolution and positioning accuracy if needed (for pile solicited under combined loading, for examples). It is therefore necessary to test reinforced fibers which can withstand this concreting phase better.

Nonetheless, further applications like the monitoring of piles at a young age for quality control purposes (by measuring of temperature inside the pile along the shaft to assess its possible change in diameter) may entice contractors to develop the use of this technology.

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