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TIME AND STRAIN DEPENDENCY OF PILE STIFFNESS: IMPACT ON PILE BEHAVIOR AND PILE LOADING TESTS RESULTS

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ABSTRACT: Static pile loading tests are carried out for different purposes: feed extended databases from which design bearing capacity of piles are derived, control the design, develop new piling methods, but also in some cases better understand the behaviour of a deep foundation submitted to additional solicitations such as temperature variations, in the case of geothermal foundations systems. These tests are conducted on any type of piles, themselves made from very different materials. For cast-in-place piles made of a combination of cementitious materials (either cement paste, mortar or concrete for example) and steel, the stiffness of the pile is a combination of the stiffnesses of the different materials. Furthermore, cementitious materials are well known to be evolutive materials, especially regarding their strength. By contrast, the strain, stress and time dependency of the stiffness of the cast-in-place piles is not so well known, and therefore generally not taken into account when analysing static pile loading tests. The aim of this publication is to impart the importance of the evolution of pile stiffness with time and under stress, through different practical examples, and comparisons are made with results obtained with more classical analysis methods.

Keywords: Deep foundations, Time-dependency, Strain-dependency, Stiffness, Pile load tests

1. INTRODUCTION

Determination of the bearing capacity is the main purpose of a static load test carried out up to the geotechnical failure, in which case the test is called a conformity test. However, another purpose can be the study of the behavior of the pile under a certain load, usually under SLS load, or slightly higher. Some tests, called control tests, are carried out on the express purpose of assessing the settlement under this load.

Furthermore, piles are often instrumented, whether it be to determine the load distribution along the shaft or to study their behavior under particular conditions such as the boring of a tunnel nearby [1] or a thermal loading [2].

Therefore, to be able to evaluate the evolution of the loads at different depths, as well as to be able to predict the settlement of a pile in any given situation, it is necessary to know its stiffness under any level of stress [3, 4].

This stiffness can be in a first approach assumed to be equal to 20 GPa for a short term solicitations or 10 GPa for long term behavior [5].

However, concrete is a non-linear elastoplastic material, and its execution conditions affect its homogeneity. Results achieved on cored samples shows the great variability of the modulus of pile concrete [6].

It is also important to keep in mind that moduli determined in laboratory are often determined using a test method non representative of the pile solicitation, with very small deformations achieved through one or multiple loading cycles [7].

Furthermore, the formulation of the concrete has to be taken into account. Following Eq. (1), it is possible to estimate the concrete modulus from its uncompressive strength [8]:

$$\mathbf{E_{cm} = 22(\, f_{cm}/10)^{0,3}} \tag{1}$$

However, it is also necessary to take into account the reinforcing steel bars of the cage inside the pile. The French standard NF P 94-150-1 [9] proposes the equivalent modulus method, taking into account the modulus of each material in the pile as well as their respective cross sectional area. This method is however often non-representative of the stiffness of the pile. Indeed, and as stated before in the case of cored samples, the values of the concrete modulus are given for a unique strain level, generally very small, leading to modulus values higher than in reality and, if used as it is, to incorrect interpretations.

2. RESEARCH SIGNIFICANCE

This paper focuses on the stress, strain and time dependency of pile stiffness: it presents several examples highlighting the importance of the adequate consideration of the stiffness variability for a correct exploitation of the results of a static load test, as well as the assessment of a pile behavior.

Indeed, better consideration of pile stiffness and its evolution, which on one hand relate to pile head displacement and on the other hand to the load distribution along the pile, will lead to an optimization of the design methods, and hence to resources and time savings.

3. STRESS AND STRAIN DEPENDENCY OF PILE STIFFNESS

3.1 Design Calculations

Taking into account the evolution of the pile stiffness in relation to the level of stress (or strain) has a big impact on the theoretical load-displacement curve.

Indeed, Fig. 1 shows the results of multiple calculations carried out with a pile stiffness kept constant along a pile, realized in a multi-layered soil, but ranging for 20 to 50 GPa. It is clear that while the impact on the bearing capacity of the pile is null, as the overall shape of the curve is minimally impacted, it is on the contrary of the upmost importance around the SLS load.

On this example, the SLS load of the pile, which would be in part defined as a fraction of the bearing capacity and by the tolerated displacement of the structure, would vary from 3800 kN to 5300 kN.

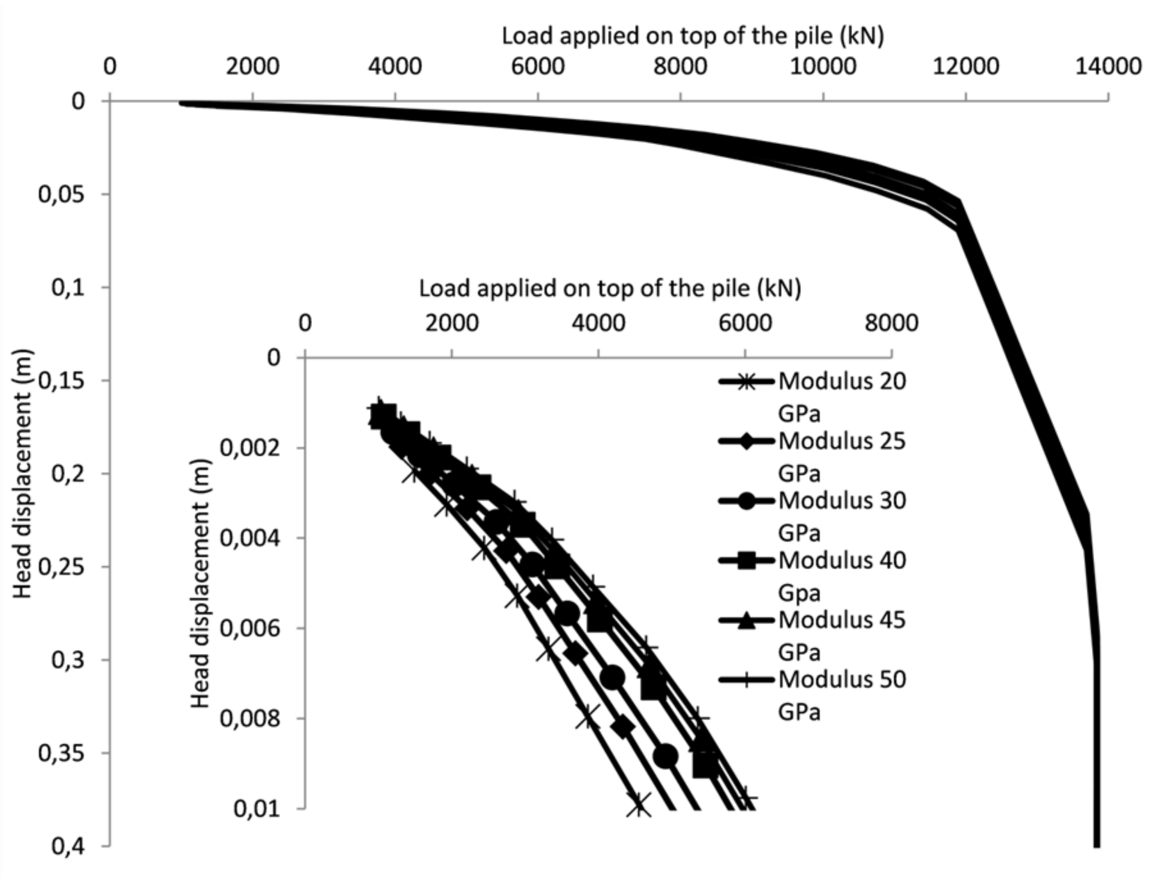


Fig. 1 Load-settlement curves for a same pile with different modulus (with a focus on the first part of the curve)

Furthermore, it is interesting to look at the theoretical mechanism of load distribution. Mobilization of the unit shaft friction q_s and base pressure q_b depends on displacement, which is due to the settlement of the pile as well as the deformation of the shaft [10].

The order of mobilization of the layers resistances also depends on the pile stiffness. Going on with the same example as before, it is clear that a higher modulus will imply a faster solicitation of the deep layers and of the base resistance, while the surface layers will be less solicited at first. This is due to the fact that with a shaft being stiffer, the shaft does not strain enough to allow for the mobilization of the q_s. Fig. 2 clearly shows this trend. It is important to note that the shape of the curves is due to the shape of the t-z curves [10].

Of course, each geotechnical model is different, so that it is difficult to generalize the impact of this behavior. However, it can be seen on Fig. 2 that the difference at the base is negligible, while for the layers above, and more importantly for the first layer, it may be important in some cases to have this information in mind.

On Fig. 2c and Fig.2d, which represent mobilization of the shaft friction under its SLS load, it is possible to note that the difference, in terms of mobilization of q_s, can go as high as 20 kPa, in this particular case, which is approximately 10% of the $q_{s;max}$.

Regarding the base resistance, under the SLS load, the effect of the modulus is negligible, as the base is barely solicited. Furthermore, from Fig. 2b, it can be concluded that the mobilization of q_b is barely impacted by a change in modulus. This can be explained by the fact that the friction of the first layers is fully mobilized approximately when the base begins to be really solicited.

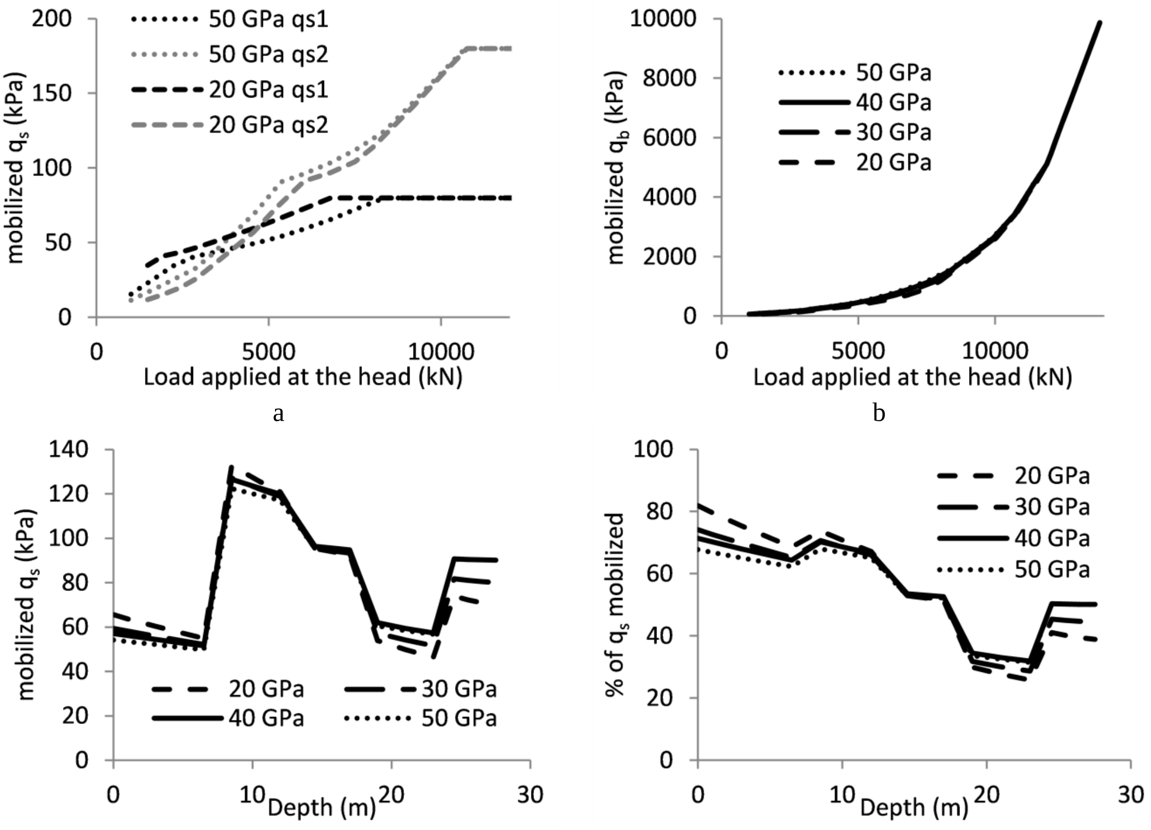


Fig. 2 Mobilization of q_s (a) and q_b (b) in function of the load applied at the head, and mobilization of q_s in function of the depth ((c) and (d)), depending on the pile stiffness

Finally, Fig. 3 shows the distribution of the axial load along the pile, under SLS load. The difference of pile stiffness between a very stiff pile (50 GPa) and a soft pile (20 GPa) results in a change of load distribution, as expected from the Fig. 2, with a maximum difference load at any given depth up to 400 kN, or 8% of the load applied at the pile head.

From what has been said above, it is clear that it is of the upmost importance to take into account the strain-dependency of pile stiffness. This is a crucial point when calculating the pile load-displacement curve. However, it is not so true when trying to assess the actual mobilization of unit shaft friction for each layer, as seen above, and even more when having in mind that the natural dispersion of this value is quite large [11].

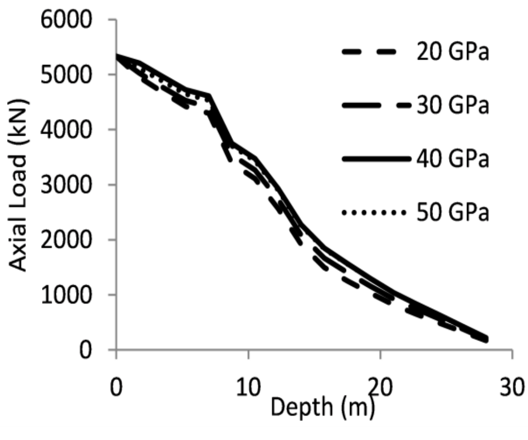


Fig. 3 Axial load distribution in a pile under SLS load, in function of its stiffness.

This variability alone has a bigger impact on the incertitude of the mobilization of the friction along the shaft than the incertitude caused by the choice of the modulus.

3.2 Pile Load Tests Analysis

As stated in the introduction, determination of the pile stiffness through laboratory tests achieved on cored samples is not representative of the actual stiffness of the pile: neither the level of stress nor the representativity of the material are pertinent in this case.

Therefore, it is mandatory to take into account the strain-dependency of the modulus to analyze the data of the strain gauges (or assimilated) used during a pile load test. To do so, multiple authors proposed different methods, summarized by [3].

Of these methods, the one proposed by [4] seems one of the most commonly used.

However, a simpler method would be to use, the first level of strain gauges to assess the stiffness of the pile, in function of the applied load. Then, knowing the cross sectional area of the pile, the modulus can be easily estimated.

Fig. 4 shows the evolution of the modulus derived from the strains measurements at the pile head, for four similar piles, realized on the same site, with the same machine and the same concrete formulation. The differences (due to slight differences in terms of realization (drilling as well as concreting phases) in the results implies that it is necessary to carry out this study every time a pile is tested, even if multiple piles are tested on the same site.

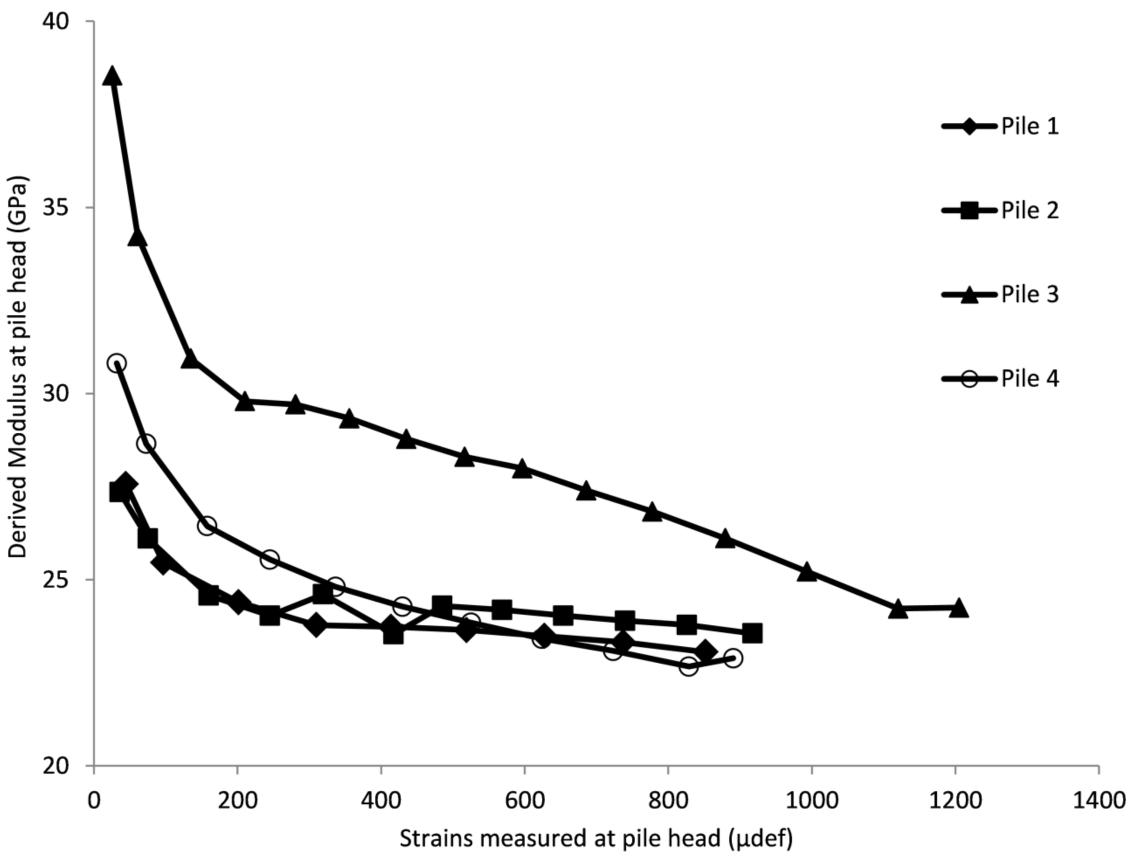
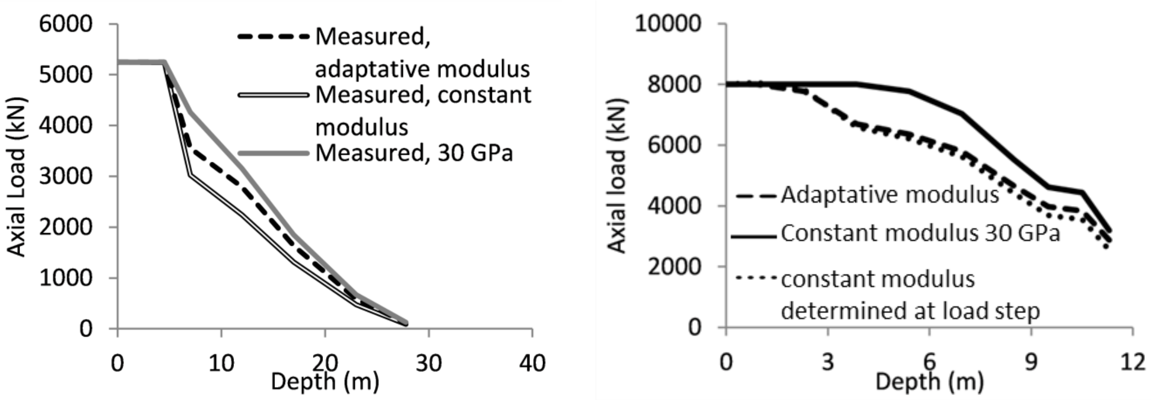


Fig. 4 Evolution of strains and modulus during load test for four similar piles realized on the same site

The purpose of an instrumented pile load test is mainly to differentiate the shaft resistance from the base resistance [12]: therefore, an accurate estimation of the load distribution along the shaft is needed. The loads at different depths are derived from the strains measurements at each level, and from the strain measured at the pile head, as stated above.

Continuing to use the pile example first used on Fig. 1, Fig. 5a shows the differences in terms of axial load distribution caused by the choice of pile stiffness. The most accurate hypothesis is to use a strain-dependent modulus to derive the axial load at each strain level: the evolution of the modulus can be established by segments or using a polynomial fit curve that relates the modulus to the strain level.

Fig. 5 shows a clear difference between the use of a modulus equal to 30 GPa (a common practice) and the adaptation of the modulus value in function of the depth (and therefore the stain level). While, under SLS load, the main difference is observed along the shaft, with almost no difference for the base pressure (as it should be, as SLS load is only a fraction of the bearing capacity), at failure, the differences are much more notable, with the base pressure being impacted too, by the modulus choice. Differences can amount for more than 1 MN at certain depths, with the solution of using a constant modulus of 30 GPa clearly over-estimating the base resistance as well as the shaft friction at the deeper levels, and therefore overestimating and underestimating q_s values by as much as 35%.



a b

Fig. 5 Axial load distribution in two piles: comparison between calculated values and measured values, with different choices of pile stiffness under SLS load (a) and at failure (b)

It is therefore of the upmost importance to analyze the data of a pile load test, having in mind the strain dependency of the pile stiffness.

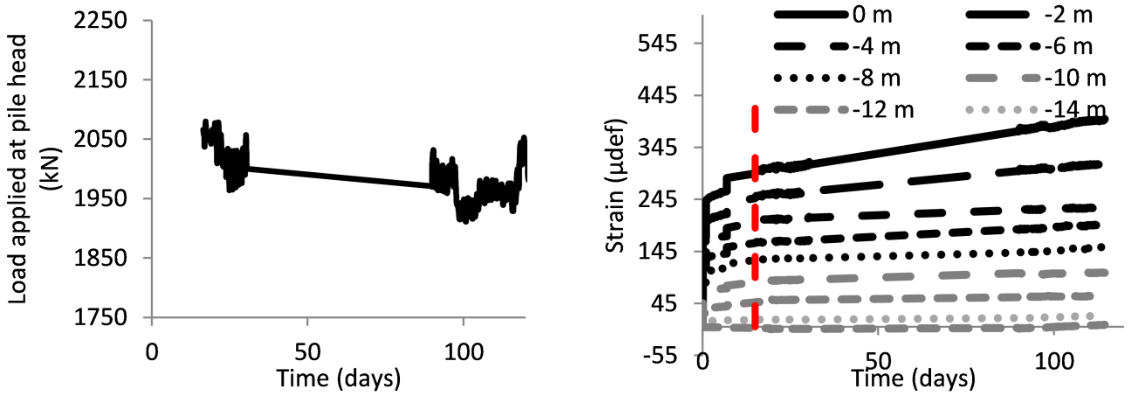
Other factors related to this issue should also be taken into account, such as the age of the pile at the date of the test or the formulation of the concrete of the test pile, as the cementitious materials are getting stiffer as days goes by, and performing a test on such a pile at a young age or with a formulation different from the formulation which will be used during the actual project could lead to the overestimation of the pile head displacement, and could therefore lead to overdesign of the piles for a project.

Fig. 1 example can also be studied from the 'time' point of view, as it relates in some way to the hardening process of the concrete.

4. TIME DEPENDENCY OF PILE STIFFNESS

4.1 Creep Strains

As stated above, concrete, as well as other cementitious materials, is an evolutive material that hardens with time. Another important point to take into account is also creep, or time dependent deformation. As piles are subjected to creep, the calculation of their deformation, and therefore of their settlement, shall take into account this phenomenon.



a b

Fig. 6 Load (a) and strains (b) in function of time, for a pile loaded under SLS load

This is partly done, for example in France, where the long-term modulus of a pile should be considered equal to 10 GPa [5], as stated above.

A pile was subjected to a constant loading (equivalent to the SLS load) for more than 4 months (Fig. 6a), and strains at different levels were monitored (Fig. 6b). The pile was loaded gradually, with load steps of equal magnitude. An automated hydraulic pump kept the load constant on top of the pile. Slight variations were caused by the differences in temperatures, which impacted the pump as well as the load cell.

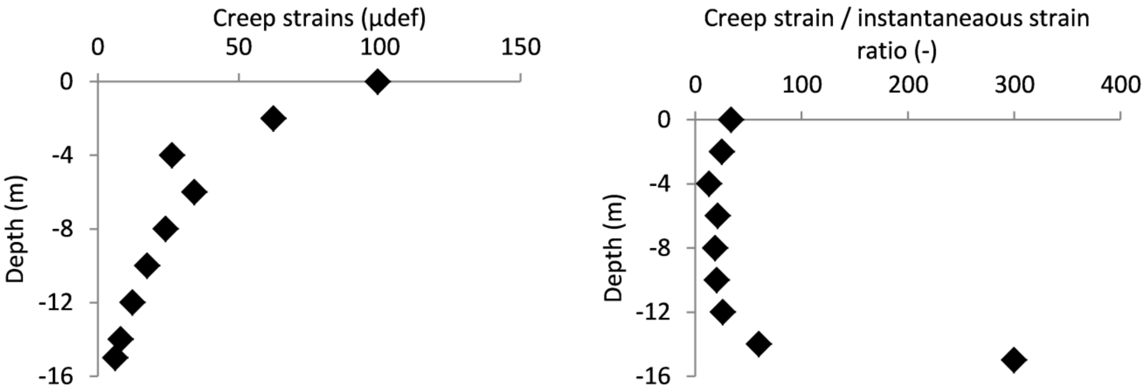
It can be seen on Fig. 6b that the strains never stopped increasing, whether at the levels close to the surface or more in depth. However, the rate of strain was different, depending on the depth: the lower the level, the slower the rate of creep.

Therefore, at the end of the four months loading period, it was seen that the pile had been subjected to creep, with a maximum accumulation of strains of 100 µm/m at the pile head (Fig. 7a).

For the lowest levels, the creep strains were much lower, as they were subjected to smaller loads. Therefore, it may seem in a first approach that the creep strains were very much dependent on the load level.

However, when looking at Fig. 7b, which represent the ratio between creep strains and instantaneous strains at different depth, it is clear that the creep is independent from the load level, as all the strain gauges (here vibrating wires) recorded the same ratio creep strains over instantaneous strains. This ratio is on average equal to twenty percent.

The two lowest levels present somewhat abnormal values because of the low level of strain they recorded to begin with: a slight variation of the strain measurement creates a larger than really measured ratio.



a   B

Fig. 7 creep strains (a) and creep strain / instantaneous strain ratio (b) at different levels, for a pile under SLS load for 4 months

From these measures, it is clear that the impact of the creep strains on the way to analyze the data for long-term pile monitoring has to be considered, and the pile stiffness as to be adjusted.

4.2 Pile Stiffness Adaptation

Fig. 8 shows the initial axial load distribution along the pile, as well as the calculated distribution after four months of loading, using the initial modulus of the pile.

Looking at the new distribution, it seems obvious that the pile stiffness needed an adjustment, so as to fit with the initial distribution. Indeed, as creep occurs, strains are increasing while the applied load stays the same (Fig. 6). Therefore, it means that the pile stiffness has to be decreased to keep the axial load distribution along the shaft constant, as the pile was not subjected to any other solicitations.

Creep strains over instantaneous strains ratio being fairly constant along the length of the pile, it is clear that the degradation of the pile stiffness must also be of the same magnitude, at every levels.

This is in accordance with the Eurocodes [8], which further state that creep should be taken into account, and that creep is dependant of the ambient humidity, the dimensions of the concrete element considered, the age at the moment of the loading and the type of cement.

For long term considerations, creep strains equal two times instantaneous strains, meaning that the pile stiffness must be degraded by a factor of three.

Incidentally, in this study, it can be seen that a loading of a pile for four months does not represent at all a long term behavior of the pile, creep strains only equaling for 20% of the instantaneous strains.

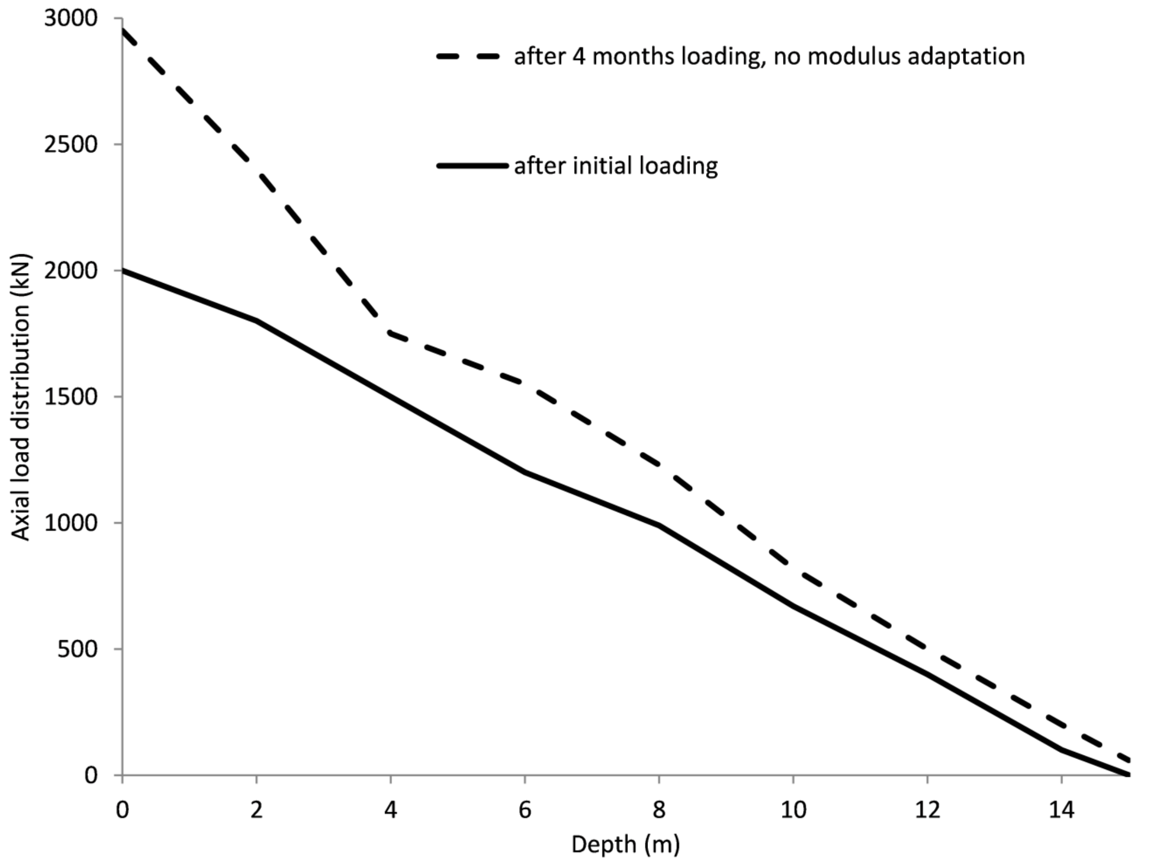


Fig. 8 Axial load distributions just after loading and after four months of loading

5. CONCLUSIONS

Static pile load tests are expensive, long tests, the results of which can considerably impact the design of the foundations of a structure or building.

Because of these high stakes, it is a priority to plan thoroughly these tests, and to carry them out in the best conditions, but also to analyze the data in the best possible way.

Taking into account the strain dependency of the material constitutive of the pile is therefore mandatory, as values given in the codes are default values, not taking into account the exact formulation of the cementitious material as well as the overall context (soil humidity, execution conditions, etc.).

Through several examples, it was shown in this publication that this is of particular importance when deriving loads from strains.

However, it is not so important for design studies such as the distribution of loads along the shaft under SLS load, for example, as other variables are much more impacting. Also, while estimating the modulus of the pile precisely is very important for the prediction of the load-settlement curve, it is not mandatory to take into account its strain-dependency.

Finally, for long-term studies of a pile behavior, the time dependency of the pile stiffness shall be taken account and studied in details. Failure to do so would systematically lead to a wrong estimation of the load distribution along the shaft, as well as that of the overall settlement of the pile.

More researches on the subject must be carried out, as the practice of reuse of existing foundations will likely increases (for economical and environmental reasons), which needs to also lead to a study of the impact of the loading history of the pile, not only in term of the evolution of the pile stiffness but also on the soil-foundation interface, for design purposes.

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