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Progress in instrumentation techniques for model piles in geotechnical centrifuge experiments

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ABSTRACT: In centrifuge physical modelling, the small-scale model pile is both the object of the study and a sensor by itself. With the addition of appropriate instrumentation, it can be used to measure the soil's local behaviour. By considering the pile as a beam, the horizontally loaded pile can generate *P*-*y* soil reaction curves used in its design. The model piles were first instrumented with strain gauges glued to the outside shaft of the tube. A pair of strain gauges diametrically opposed on the same section measure directly the bending moment. However, these gauges must be protected by a seal that affects the roughness of the pile, a key parameter which governs the behaviour of its interface. In some cases, the gauges can be glued inside the shaft of the tube. However, in both cases, the inside of the tube, housing wires, must be close-ended. More recently, the democratisation of optical fibres has seen instrumentation evolve. Bragg grating technology allows several strain measurements to be taken on a single fibre. This fibre, glued along the length of the pile, measures the axial deformations at different depths. The fibre, emerging above the ground level, can be used to study open-ended tubes. Several examples are presented: i) piles with several slenderness ratios, ii) monopiles driving in-flight, iii) very large monopiles, and iv) piles loaded horizontally in different directions.

1 INTRODUCTION

The horizontal loading of piles generally results from external excitations produced by waves, current, wind, a ship pulling on a mooring line, etc., such as those experienced by offshore structures. That is why the oil and gas industry was one of the first, in the 1970s, to demand rules for dimensioning horizontally loaded piles (Reese et al, 1974). The *P*-*y* method uses the beam theory to represent the pile and a series of non-linear springs to model the soil. The transfer curves of these springs are called *P*-*y* curves and represent the reaction of the soil due to the lateral pile displacement. These curves depend on the nature of the soil and its depth.

To determine experimentally these curves, in-situ tests on instrumented piles can be carried out. These tests are expensive and often difficult to analyse. Because of the heterogeneity of the soil in place, the double differentiation of the bending moment which gives the soil reaction is very sensitive. Another possibility is to carry out tests on small-scale model piles performed in centrifuge. In this way, the model pile is subjected to stresses similar to those experienced by the prototype it models.

The geotechnical centrifuge at the Gustave Eiffel University (formerly LCPC, then IFSTTAR) was

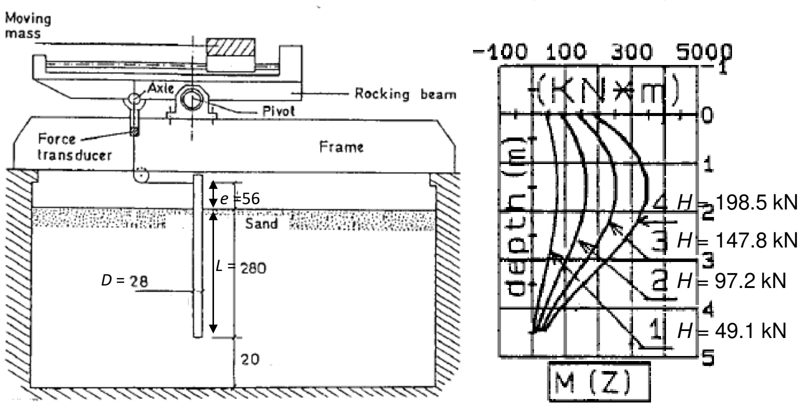

Figure 1. Set-up and model 1/17.8 dimensions in mm (left) – Bending moment profiles (right) from Bouafia and Garnier (1991).

inaugurated in 1985. With a diameter of 11 m and a capacity of 2 tonnes at 100*g*, it is a large beam centrifuge especially well suited to study deep foundations. The centrifuge acceleration gradient is very small within the depth of the model. The first study performed in this facility on a laterally loaded pile was published in 1991 by Bouafia and Garnier. In their study, 12 pairs of strain gauges were mounted on the front and the back of the outside shaft of an aluminium tube. The strain gauges were protected by a silicone membrane surrounding the pile. The set-up, tested at 17.8*g* is presented in Figure 1 as the bending moment profiles for 4 different horizontal loads. Bouafia and Garnier (1991) succeeded to get *P-y* curves. However, the soil stiffness was several times smaller than those recommended by standards. The authors explained this discrepancy by the difference between the deformability of sands in the field and sands reconstituted in the laboratory at the same density.

From this early stage, this paper is focused on the evolution and progress of the instrumentation technique of model piles for horizontal pile loading in geotechnical centrifuge. First, two examples of bending moment profiles will be presented obtained from a pile with strain gauges glued outside and inside the pile shaft. Then, the recent development in use of the optical fibre with the Bragg grating technology will be introduced: modelling of open-ended monopiles, installation by impact hammering and multi-directional loading.

2 PILE WITH STRAIN GAUGES

Using the beam theory, the bending moment is calculated from the axial strain along the pile using its stiffness and moment of inertia. Pairs of strain gauges are glued diametrically opposed outside or inside the pile shaft. The two opposed strain gauges are wired in a half-bridge configuration to measure directly their difference and then the bending moment.

2.1 Strain gauges outside

For strain gauges glued outside the pile shaft, the wires from the half-bridge enter the pile through a small hole drilled in it and emerge at the pile head. In this way, the pile is full of wires and has to be close-ended. On the outside shaft, a flexible silicone membrane protects the strain gauges which increases the pile diameter by around 6% without increasing the pile flexural rigidity.

In Figure 2 are presented the bending moment *M* profiles measured for a flexible pile (with diameter *D* = 1.8 m, slenderness ratio *L*/*D* = 22, eccentricity ratio *e*/*D* = 37.2) tested at 100g in dry sand. The model pile is instrumented with 20 pairs of strain gauges. For long flexible piles, these results are well known: i) *M* reaches a maximum value, ii) *M* decreases to a negative value, and iii) finally, *M* comes back to zero near the pile end. The depths of these maximum and minimum values do not depend on the load.

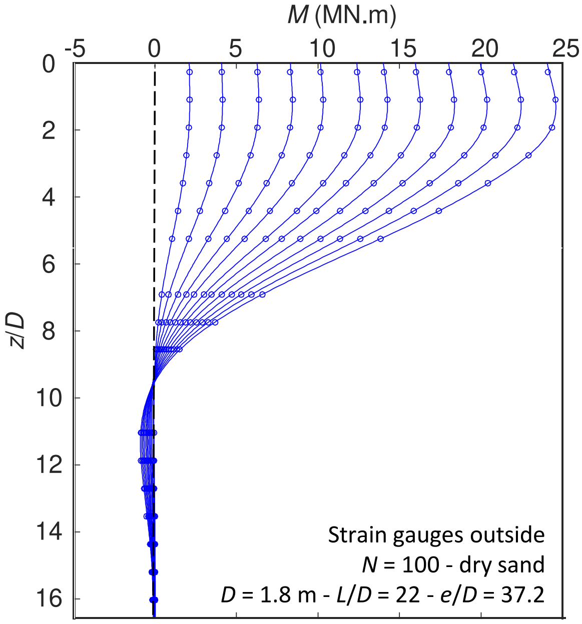

Figure 2. Bending moment profiles for a long pile instrumented with stain gauges glued outside the shaft.

One limitation of model piles instrumented with strain gauges glued on the outside shaft is the flexible silicone seal around it. This seal is not strong enough to protect strain gauges during a pile installation in-flight. The sand friction around the pile shaft is too high. This type of model piles can only be installed at 1*g* or during the sand pluviation. However, the installation of the model pile is a key point on which its subsequent behaviour depends. This is especially important because the response of horizontally loaded piles is not enough stiff in centrifuge.

2.2 Strain gauges inside

More recently, El Haffar (2018) succeeded in glueing strain gauges inside the pile shaft. This pile can be installed in flight at a constant displacement rate, and then horizontally loaded without stopping the centrifuge. In this way, the stress state generated around the pile during the installation is conserved for the horizontal loading.

In Figure 3, are presented the bending moment profiles for a close-ended model pile (*D* = 1.8 m, *L*/*D* = 11, *e*/*D* = 1.7) tested at 100g in dry sand. This model pile is instrumented with 16 pairs of strain gauges glued inside the pile shaft. For three loadings, the *M* profiles obtained for the pile installed at 1*g* are compared with the ones installed at 100*g* (without

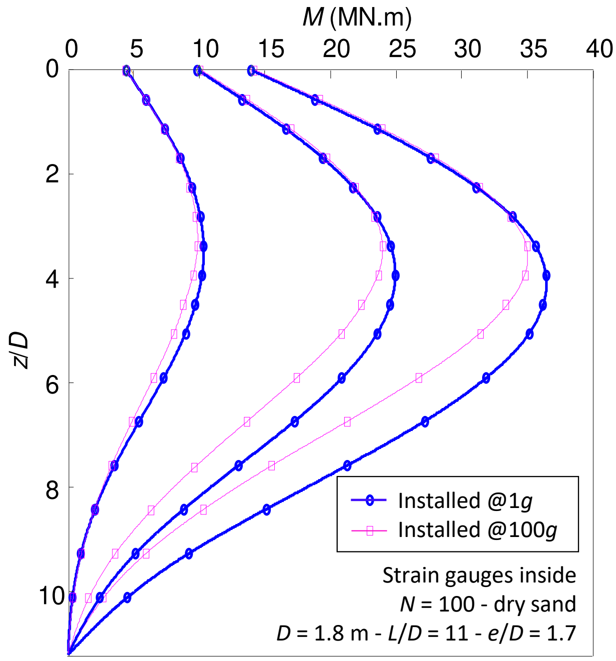

Figure 3. Bending moment profiles for a pile instrumented with strain gauges glued inside the shaft – difference due to the installation in flight.

stopping the centrifuge). For the pile installed in flight, *M* max. is lower and is reached at a lower depth. This means that the *M* profile curvature is more pronounced as the soil reaction *P*. By installing the pile in flight, its horizontal response becomes stiffer.

3 OPTICAL FIBRES WITH FBGS

3.1 Fibre Bragg Grating Sensor (FBGS)

One limitation of using strain gauges to instrument pile model is that the pile is full of wires and then close-ended. With the development of monopile foundations for offshore wind turbines, a new way of instrumenting piles had to be found. At the same time, the use of optical fibres OF became more widespread. The Fibre Bragg Grating Sensor FBGS makes it possible to interrogate the fibre at a precise location to get its wavelength. The wavelength variation is directly related to the fibre deformation. It is called an optical strain gauge.

The limitations of the use of FBGS are: i) up to 15 gratings can be interrogated on the same fibre, ii) the minimum distance between two gratings is about 25 mm, iii) the maximum data sampling is 5 kHz, iv) the optical fibre is very sensitive to temperature.

To easily position and glue OF on the pile, it is recommended to machine a groove in the tube thickness. The OF diameter is only 200 µm, so the groove does not need to be deep. If more than 15 FBGS

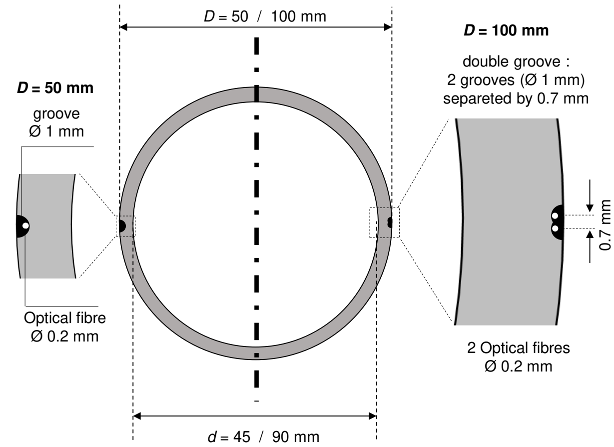

Figure 4. Cross section of the instrumented model monopiles with FBGS in a groove for D = 50 mm (left) and in a double groove for D = 100 mm (right)

are required or the spacing between two FGBS has to be lower than 25 mm, two grooves can be machined side by side. Each groove holds one OF by positioning them staggered. A two-component glue protects also the OF. In this way, an open-ended pile instrumented with FBGS can be installed in flight without damaging the optical fibres.

In Figure 4, are presented the examples of two model monopiles instrumented with FBGS: i) on the left, a tube with *D* = 50 mm (a thickness equal to 2.5 mm) and one OF inside a semi-cylindrical groove of 1 mm large and 0.5 mm deep, up to 12 FBGS levels are located on this OF (Li et al., 2020) and ii) on the right, a tube with *D* = 100 mm (a thickness equal to 5 mm) and two OF inside two semi-cylindrical grooves of Ø 1 mm, separated by 0.7 mm centre-to-centre distance, 23 FBGS levels located on these 2 OF. Horizontal loading tests on these two model monopiles are presented in the next subsections.

3.2 Model monopiles with several *L*/*D* ratios

In this subsection, four tests performed at 100 g in saturated sand are presented using the model monopile with *D* = 50 mm (presented in section 3.1) installed at four different embedded lengths: 150, 250, 350, 450 mm (i.e. 3*D*, 5*D*, 7*D* and 9*D*) (Li et al., 2022). The horizontal loading is applied at 500 mm above the ground level (*e* = 10*D*) through an electric actuator by pushing a steel rod that crosses the model piles diametrically. A load sensor measures the load between the actuator and the fork. In front of the pile, three LASER displacement transducers are located on a support beam at several heights to measure the pile deflection above the ground level. The set-up is presented in Figure 5 for the 9*D* model monopile.

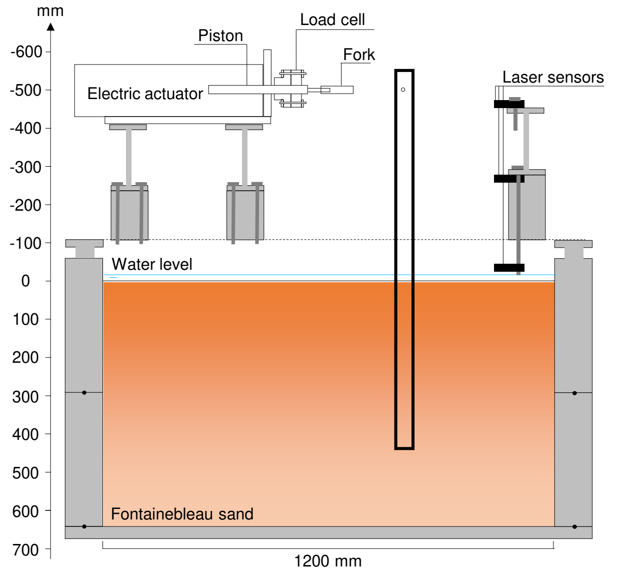

Figure 5. Experimental set-up for horizontal loading of an open-ended monopile at 100g : D = 50 mm - L/D = 9 - e/D = 10.

Figure 6 presents the axial strains measured by the FBGS along the depth for *L/D* = 3, 5, 7 and 9. These results show different behaviours in the compression side (negative values) than in the tension one (positive values). In the first half part of the pile, there are more compressive strains than tensil strains, whereas in the second half, the situation is the opposite, tensile strains are more prominent than compressive strains. This difference is more pronounced as the slenderness ratio decreases. For *L/D* = 9, there is nearly no difference, showing that the difference (i.e. the tension-compression asymmetry) is not due to troubles with the instrumentation or the set-up but to the monopile behaviour itself.

For these four *L/D* ratios, the shape of strain profiles of the side in compression are rather similar. The difference is more pronounced for the strain profiles in extension. For low slenderness ratios, in the back of the pile at the toe, the soil reaction is very high. It may induce large boundary effects. The pile is too short to compensate for these effects, the pile can no more be considered as a beam.

3.3 Model monopiles installed by hammering in flight

The horizontal response of model piles in centrifuge is not enough stiff compared to in-situ observations (Bouaffia and Garnier, 1991). The sand deposit of the model sample can be one cause. But the method of pile installation has also to be investigated and accurately simulated as it influences the pile on its long-term behaviour. Open-ended model monopiles instrumented with FBGS can be installed in-flight without damaging the OF. Maatouk et al. (2022a) developed an impact hammer to install, at 100*g*, a model monopile of 50 mm large to an embedment depth of 5*D* in saturated sand. This set-up allows to subsequently horizontally load the monopile at 5*D* above the ground level without stopping the centrifuge.

Figure 7 presents the axial strains measured by the FBGS along the depth for horizontal loading tests of two monopiles installed in two different ways: i) one installed at a constant displacement rate at 1*g* and ii)

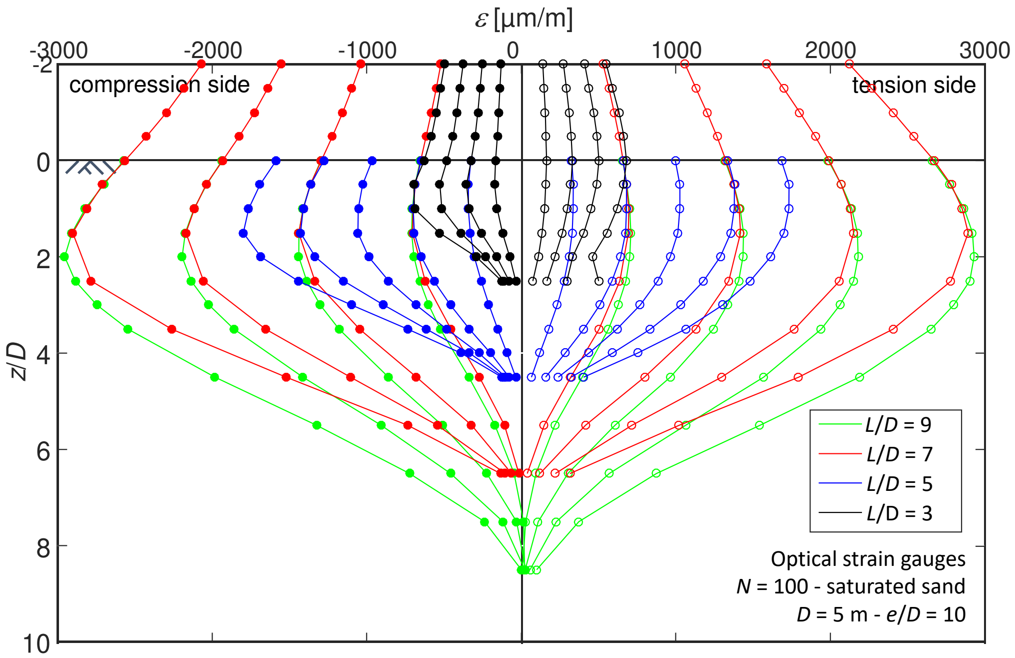

Figure 6. Axial strain profiles in compression and tension sides of model monopiles instrumented with optical strain gauges - impact of the L/D ratio.

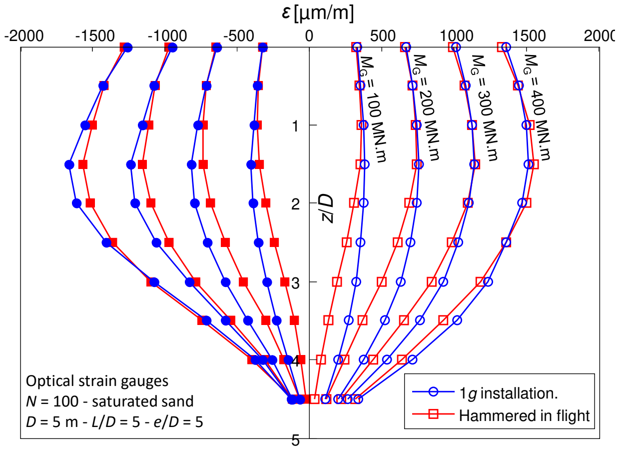

Figure 8. Axial strain profiles in compression and tension sides of model monopiles instrumented with optical strain gauges – impact of in-flight hammering.

the other is impact-driven at 100*g*. In both cases, after installation, no plug has been measured. Four loading states, corresponding to a bending moment at ground level M_G = 100, 200, 300, and 400 MN.m are compared. As the applied load increased, normal strains within the monopile increased as well. Under the same value of M_G, normal strains in both tests increased with depth until reaching a maximum at the fourth FBGS ($z = 1.5D$), below which they continued to decrease progressively to almost zero near the monopile base. However, the pile installed in flight featured amplitudes of axial strain lower than those of the pile installed at 1*g*. At the same depth, an asymmetry was noted between compression and tension, and became more significant at the monopile base.

As observed in section 2.2 for a close-ended 10*D* long pile installed in flight at a constant displacement rate, the monopile installed by hammering inflight exhibits more curvature stain profiles than those measured for the pile installed at 1*g*. It means that the soil reactions *P* are stronger and the monopile response is stiffer. Once again, these results underline the importance of simulating as closely as possible the pile installation to study its horizontal response (Maatouk et al., 2022b).

3.4 An example of modelling of models

The "modelling of models" approach consists of modelling the same prototype with several small-scale models tested at different acceleration *g* levels. The main objective of this technique is to study potential scale effects.

In this subsection are presented two small-scale models at 1/50th and 1/100th of the same prototype tested in centrifuge at 50*g* and 100*g* respectively. The prototype monopile dimensions are: $D = 5$ m, $L/D = 5$ and $e/D = 5$. These two model monopiles are installed at a constant displacement rate at 1*g* in saturated sand. On the 1/50th model, the monopile dimensions are quite large: $D = 100$ mm and $L = 500$ mm. It allows to instrument 25 levels of FBGS, 2.5 times more than one in the 1/100th model. Moreover, there are more levels of FBGS located near the monopile base. This particularity has been chosen to measure a more accurate bending moment profile near the base to try to estimate more precisely the moment and the shear base reaction which are key parameters of the monopile behaviour.

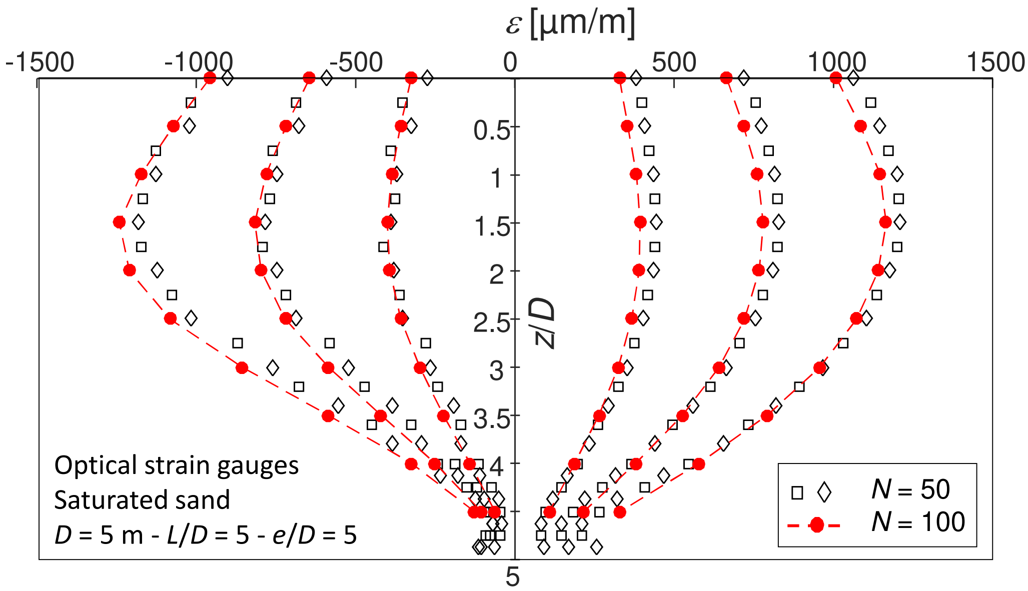

Figure 7. Axial strain profiles in compression and tension sides of model monopiles instrumented with optical strain gauges – modelling of models.

For both tests, strain profiles are presented in Figure 8 for M_G = 100, 200 and 300 MN.m. In absolute value, the shapes of profiles in compression and tension are rather close to each other even if there is a none negligible asymmetry. Axial strains increase with the depth to reach a maximum value around z = 1.5D. Under this depth, this strain intensity decreases.

For the 1/50th model, the strain (in absolute value) measured at the two deeper FBGS levels (at z = D/4 and D/8 from the base) re-increase significantly near the base. This peculiar behaviour has no physical meaning. It would mean there is a final re-increase of the bending moment and then a negative shear at base: The monopile base would be loaded by something (as it is imposed at the loading point by the actuator). The axial strains measured by the FBGS located in this area are too close to the base to be analysed using the beam theory. Under D/2 from the base, cross sections are too close to the beam end termination. There are too many boundary effects in this area. To better understand the behaviour in this area (shear and moment base reactions), the Author recommends using numerical modelling.

3.5 Large model monopiles

Using the large model monopile (D = 100 mm) presented in section 3.4, it has only been installed in saturated sand on the embedding length of 3D and tested at 100g. In this way, the prototype corresponds to a 10 m large monopile embedded on 30 m.

In Figure 8, are presented the axial strain profiles measured by the two OF in compression and tension. As the model monopile is instrumented on 5D long, the strain profiles can also be analysed until 2D above the ground level. The loading point is located at 5D. The stain profiles between the ground surface and z = 2.5D in the soil have been fitted by a 5th-order polynomial. As explained in the previous sub-section, the two last levels (too close to the base) are not taken into account. Once again, for this low L/D ratio equal to 3, the stain profile shapes in compression and extension are very different. The maximum bending is obtained for z = 0.75D.

In dotted lines, the theoretical axial strain profiles expected by the beam theory are plotted above the ground level (when the monopile is not subjected to soil reaction). In absolute value, the strain profiles measured in extension are higher than the one predicted by the beam theory whereas it is the opposite in compression. However, the difference between these two profiles would give the right bending moment. This observation is hardly explainable because it would also mean that there is a variation of axial load in the monopile between the loading point and the ground level even though the monopile is in the air or water (without any friction along its shaft). The reason for this asymmetrical behaviour would rather be due to the propagation of boundary effects at the loading point (but also at the base) all along the monopile. This boundary effect cannot be dissipated within the monopile length because of its low slenderness ratio.

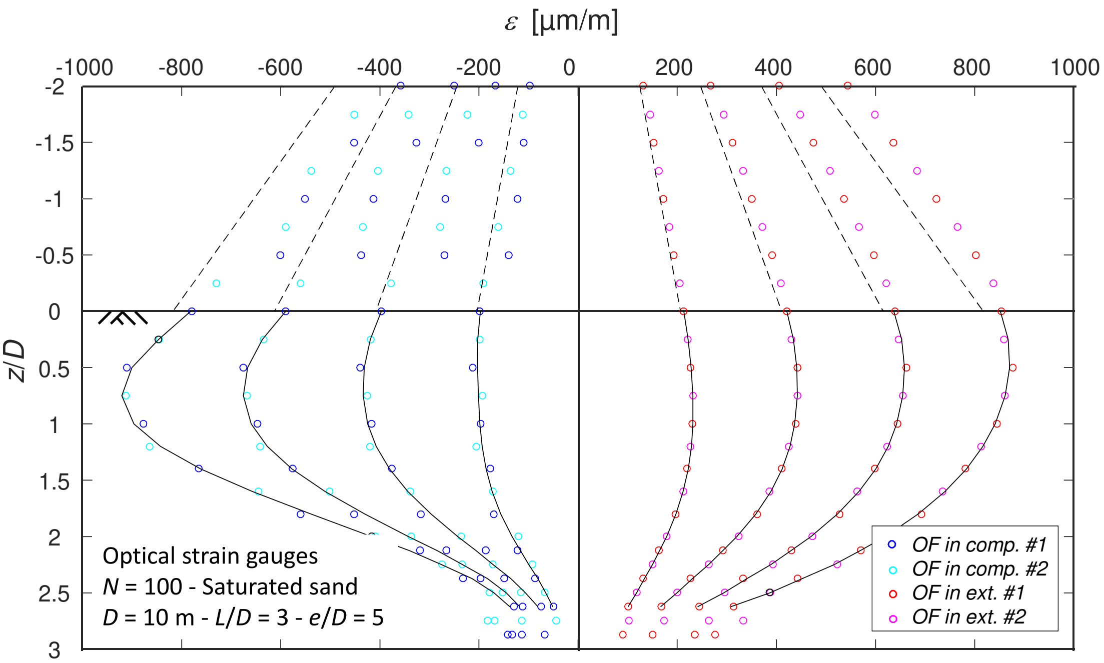

Figure 9. Axial strain profiles in compression and tension sides of model monopiles instrumented with optical strain gauges in a double groove – example of a large short monopile L/D = 3.

4 PILE INSTRUMENTATION FOR MULTI-DIRECTIONAL LOADING

Geotechnical engineers are increasingly confronted to the problem of multidirectional horizontal loading. For instance, the first shared anchors for floating offshore wind turbines have already been installed in Norway. These anchors are loaded in several directions which is new for anchoring systems (generally connected to a single mooring line). To study shared anchor piles, Zabatta et al. (2024) have developed a new set-up with three actuators to pull three mooring lines every 120°. To study the anchor pile behaviour in the horizontal plane, 2 pairs of 2 OF diametrically located at 90° are mandatory (i.e. 4 OF) every 90°. Only 2 OF at 90° would have been enough if the pile behaviour had been symmetrical. However, the asymmetrical pile behaviour has been underlined several times in the previous section. Moreover, to compensate thermal effect on OF, it is recommended to use it as diametrically opposite pairs.

In Figure 10 are represented the strain profiles obtained for two horizontal loading tests: i) one with the OF in line with the loading ((a), (b), (c) and (d)) and (ii) the other with the OF inclined at 45° from the loading ((e), (f), (g) and (h)). In Figure 10.(a) are plotted the strain profiles measured for the in-line OF as usually done. In Figure 10.(b) are plotted the strain profiles measured for the perpendicular OF. These OF are on the neutral axis of the pile. Their amplitudes are small but not null. They are positive (in extension) above the pile rotation centre and negative (in compression) under the pile rotation centre. To better analyse these results, the half difference ($\Delta\varepsilon/2$) and the half sum ($\Sigma\varepsilon/2$) of the diametrically opposed OF are plotted in Figures 10.(c) and 10.(d). Using beam theory, $\Delta\varepsilon/2$ gives the shapes of the bending moment profiles M and $\Sigma\varepsilon/2$ the ones of the axial load profile N. In the in-line direction, M shapes are very consistent. In the cross direction (at 90° from the loading direction), values represent, at maximum, less than 3% of the in-line bending moment. It could be due to the uncertainty of the loading direction (within a few degrees). The N shapes and amplitudes are rather similar in the in-line and cross directions. From the ground level, first in tension, then in compression. Near the base, they are null in the cross direction but positive (in extension) in the in-line direction. The differences observed at the pile loading point and the base could be due to boundary issues and limitations of the beam theory in these areas.

In Figures 10.(e) and 10.(f) are plotted the strain profiles measured for the OF at 45°: two in the tension side (positive values) and two in the compression side (negative values). These 4 profiles are very close to each other (in absolute value) as shown by the half difference $\Delta\varepsilon/2$ and the half sum $\Sigma\varepsilon/2$ plotted in Figures 10.(g) and 10.(h). The difference between the

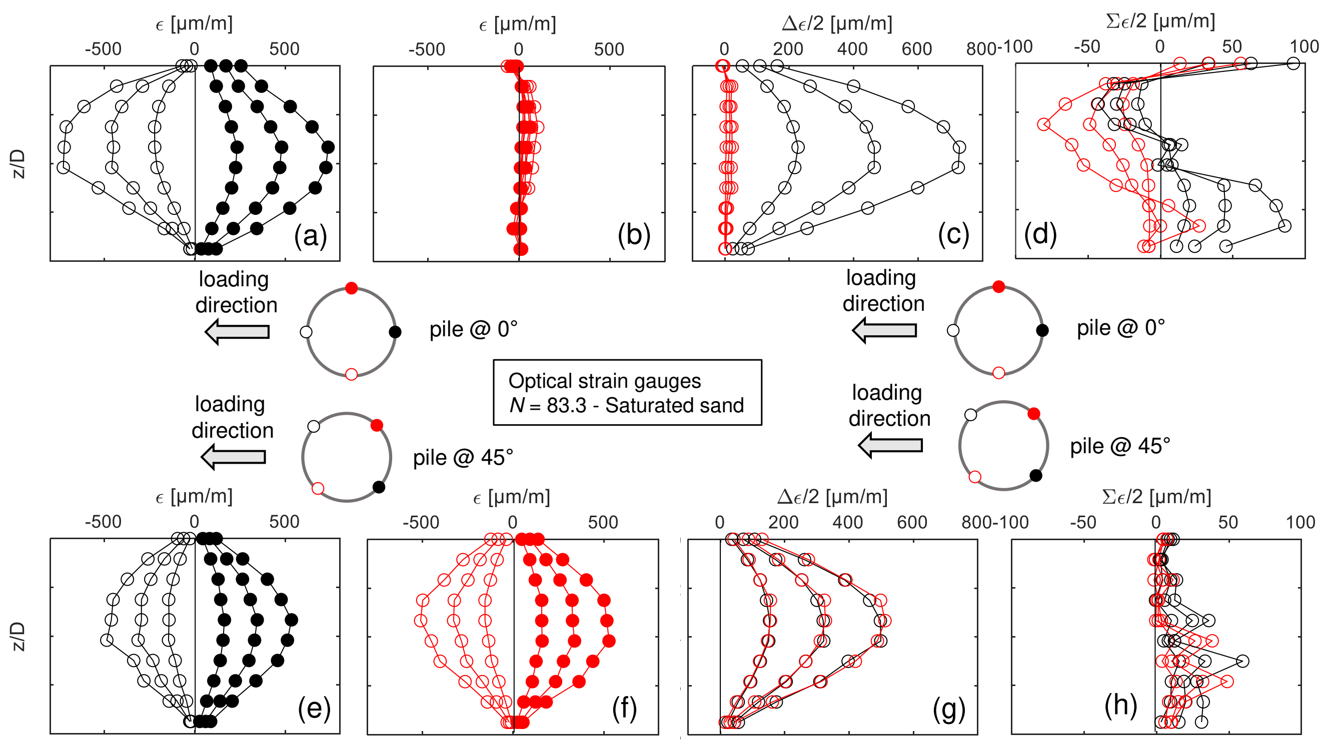

Figure 10. Axial strain every 90° of a model pile instrumented by 4 OF loaded in the direction of these OF ((a), (b), (c) and (d)) and at 45° ((e), (f), (g) and (h)).

compression and tension sides is much lighter (nearly null) than the one measured for the in-line loading direction. This symmetrical behaviour also demonstrates that the loading has effectively been applied at ±45° from the OF directions.

To calculate the bending moment in the loading direction with the OF at 45°, $\Delta\varepsilon/2$ has to be multiplied by $\sqrt{2}$. For this reason, in Figure 11, the average of the half difference $\Delta\varepsilon/2$ for OF at ±45° is multiplied by $\sqrt{2}$ and then compared to the one obtained for the in-line configuration. The results are very consistent and prove that this pile instrumentation with 4 OF every 90° is very well adapted to study multidirectional loading.

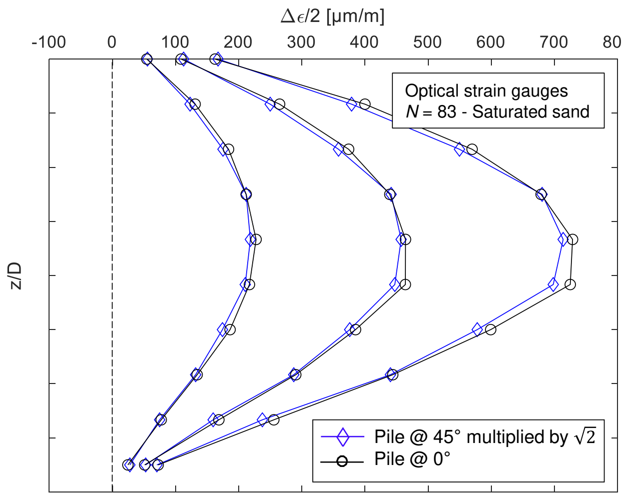

Figure 11. Comparison of the half-difference strain profiles between the configuration in-line and the one at 45°.

5 PERSPECTIVES

The Bragg grating is not the only technology using the OF. Rayleigh scattering-based distributed fibre sensors are becoming more often used for measurements of strain change. This technology allows mapping the strain (and temperature) fields with sub-millimetre spatial resolution. However, spatial resolution is not the main issue in instrumenting a model pile as the size of the model cannot be reduced indefinitely without avoiding scale effect. Moreover, the densification of the FBGS near the pile base (exposed in section 3.4) did not bring novelties as the boundary effects are predominant in this area.

In addition to the bending moment, the other important parameters to analyse the pile behaviour are also its rotation and deflection. They are obtained by successive integrations of the bending moment and need two constants. To have the best accuracy, these two constants have to be taken as far away as possible, for instance, one at the base and one at the ground level. Unfortunately, for short piles, the deflection is not null at the base. So, these two constants may be taken at ground level. A promising way to collect these data is the use of image processing. Several targets can be located along the pile above the ground level. The global accuracy of this method has still to be improved. Another way could be the use of inclinometers inside the embedded length of the pile. This practice is already in place on-site. The size of these sensors is still bulky to be installed on a small-scale model. Nevertheless, their size may be reduced in the near future.

6 CONCLUSIONS

Performing small-scale tests in a geotechnical centrifuge is a very suitable way to study pile foundation behaviour subjected to horizontal loading. The axial strain profiles of the model piles have to be measured to get *P-y* curves using the beam theory. In the 80s, the model piles were instrumented with strain gauges connected in half-bridges glued on the outside shaft of the pile and protected by a silicon seal. The pile was close-ended because full of bridge wires. These first tests gave too soft *P-y* curves. One possible way to increase their stiffness was to install the pile in the same way as it is performed on-site.

For this purpose, more recently, model piles were instrumented with strain gauges glued inside the pile shaft. The model piles were installed in flight at a constant displacement rate and then horizontally loaded without stopping the centrifuge acceleration. The results obtained using this installation method show much stiffer *P-y* curves. Nevertheless, these new *P-y* curves weren't yet enough stiff compared to standards.

In the early 2010s, the issue of monopile foundations for offshore wind turbines became critical. To study these open-ended piles, small-scale monopiles were instrumented with optical fibres using Bragg grating technology. These fibres were glued inside grooves. They measured directly the axial strain, not the half difference as it was previously done with strain gauges mounted in half-bridges. These shorter piles exhibited a very asymmetrical behaviour between the tension and compression sides. A tentative has been made to densify the instrumentation near the monopile base to get access to the shear and moment base reactions. Unfortunately, the boundary effects were predominant in this area to give any significant insight.

As done for slender piles, model monopiles were installed in-flight by impact hammering and subsequently horizontally loaded without stopping the macro-gravity field. Modelling the installation method in centrifuge, horizontal loading test results were very consistent with the ones predicted by standards.

Nowadays, multidirectional pile loading has also become a key area of research with the development of shared anchors for floating offshore wind turbines. To study this peculiar behaviour, the model pile can be instrumented by 4 optical fibres, every 90°. In this way, the horizontal loading direction can even be determined accurately.

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