The paper was published in the proceedings of the 10th International Conference on Physical Modelling in Geotechnics and was edited by Moonkyung Chung, Sung-Ryul Kim, Nam-Ryong Kim, Tae-Hyuk Kwon, Heon-Joon Park, Seong-Bae Jo and Jae-Hyun Kim. The conference was held in Daejeon, South Korea from September 19th to September 23rd 2022.

***Physical Modelling in Geotechnics***
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# Use of optic fibre technology to measure strain on laterally loaded piles

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**ABSTRACT:** Optic fibre technology has been used to obtain measurements of strain on full scale foundations, and particularly for field testing of piles. Its use in physical modelling is being studied by various research institutes across the world, as optic fibre technology may provide benefits over more traditional instrumentation, particularly in regard to the close spacing between sensors which can yield quasi-continuous monitoring of strain along the length of a model. However, challenges remain, such as the influence of temperature and the potential for noise in the recovered data. This paper provides a comparison between a laterally loaded flexible pile instrumented with optic fibres (Fibre Bragg Gratings) and a pile instrumented with traditional pairs of strain gauges. Aspects such as continuity and smoothness of strain profile, change in pile external diameter and stiffness due to epoxy coating of the sensors, and similarity of the derived p-y curves from both types of instrumentation are discussed. It was found that instrumenting flexible piles with optic fibre yields results that are similar to strain gauges, but with the added benefit of faster installation, less added stiffness due to epoxy coating and more data points along the length of the pile.

**Keywords:** Optic Fibre, Strain Gauges, Fibre Bragg Gratings, Laterally Loaded Piles, Centrifuge.

## 1 INTRODUCTION

Lateral soil-pile interaction is routinely modelled using non-linear Winkler springs called p-y curves (API, 2014), which are a relationship between soil reaction ($p$) and lateral displacement ($y$). A recent case study (Guevara et al., 2022) found that p-y curves perform well in predicting the soil-pile lateral behaviour of flexible piles, and that further improvement relies on more accurate estimation of the curves for given materials. Many authors (Matlock, 1970; Reese & Welch, 1975) have published empirically derived p-y curves from field tests of instrumented piles, while others (Bransby, 1999; Zhang & Andersen, 2017) have proposed scaling to derive p-y curves from simple shear tests. In addition, physical modelling can be used to estimate p-y curves by instrumenting a model pile with sensors that measure strains when the pile is loaded laterally.

Measured strain is converted to bending moment ($M$) using the rigidity ($EI$) of the pile and the pile external diameter ($d$). A function ($M(z)$) is then fit to the data, where $z$ measures the length down the pile ($z = 0$ is the soil surface). Polynomial approximations, spline interpolation and B-spline interpolation (spline smoothing) have been used as fitting functions by previous authors to derive p-y curves from the data.

To obtain soil pressure ($p(z)$), the bending moment function is double differentiated along the pile length:

$$p(z) = \frac{d^2M(z)}{dz^2} \tag{1}$$

and double integrated to obtain lateral deflection ($y(z)$) along the length of the pile:

$$y(z) = \frac{1}{EI}\iint M(z)dz.dz \tag{2}$$

The most commonly used sensors for determining bending strains along a model pile are pairs of strain gauges arranged in half-bridge configuration – with each pair placed diametrically opposite to each other in the direction of bending strain. This configuration compensates for temperature variations but does not allow to measure axial strains.

A limitation of strain gauges is the spacing between them, which reduces the number of data points measured along the pile. In addition, each strain gauge requires a cable to run along the pile to an electronic connector, with both gauge and cable requiring an epoxy cover to protect them from moisture. This increases the external diameter of the model as well as its rigidity, affecting the behaviour of the pile.

Optic fibre technology can be used to monitor deformation and integrity of engineering structures, with recent applications including field (Buckley et al., 2020; Burd et al., 2019) and centrifuge (Song et al., 2021) testing of piles. These recent applications have used Fibre Bragg Grating (FBG) sensors, which comprise an optical fibre onto which gratings are inscribed. When light travels along the fibre, a specific spectrum is reflected by the grating, which changes with strain in the fibre. By measuring the difference in wavelength between the original and strained fibre, the level of strain at the specific location of each grating can be obtained.

The strains measured with the fibre on a laterally loaded pile will include bending, axial and temperature strains. Temperature corrections can be complicated to implement but can be overcome if two diametrically opposite fibres are attached along the pile.

A key advantage of optic fibre technology is the short spacing between the grating sensors (3.2 mm in this study) which enable measuring of strain at more locations along the pile. This provides a more complete strain profile, reducing the risk of missing important information when a sensor fails.

Because the fibre is the only sensor that needs to be attached, and its diameter is small (200 μm in this study), the epoxy layer required to cover it has only minimal effect on pile diameter, reducing the impact on rigidity.

This paper compares results from a laterally loaded flexible pile instrumented with an optic fibre (and FBG) with pile instrumented with traditional pairs of strain gauges. Aspects such as continuity and smoothness of strains profiles, change in pile external diameter and stiffness due to epoxy coating of the sensors, and similarity of the derived p-y curves from both types of instrumentation are discussed.

## 2 TEST SETUP

The experimental data was obtained from centrifuge testing of a laterally loaded pile installed in reconstituted soft (normally consolidated) silt, at an acceleration of 80g. The undrained strength gradient of the soil measured with T-bar (Stewart & Randolph, 1991) was 1.65 kPa/m. The pile was jacked into position at 1g, while at the same time using a rotating drilling auger (in the pile) to remove the soil from inside the pile and preventing plugging during installation. Once installed to the required embedment depth, the auger was carefully removed by rotating it on the opposite direction and pulling backwards, and a small (aluminium) plug was placed inside the pile to balance vertical stress at tip level (and stop inflow of soil).

### 2.1 Instrumentation and sensors

The test setup (Fig. 1) comprised an aluminium pile instrumented with either strain gauges or optic fibres, each covered with sufficient epoxy to protect the sensors. The pile head was hinged to allow rotation (zero moment), but with vertical displacement restricted at the hinge pin. The embedded depth of the pile was 18.24 m and the hinge was located 3.36 m above the soil surface. Lasers were used to measure pile head displacement and rotation, and a load cell used to measure the applied horizontal force ($F_h$).

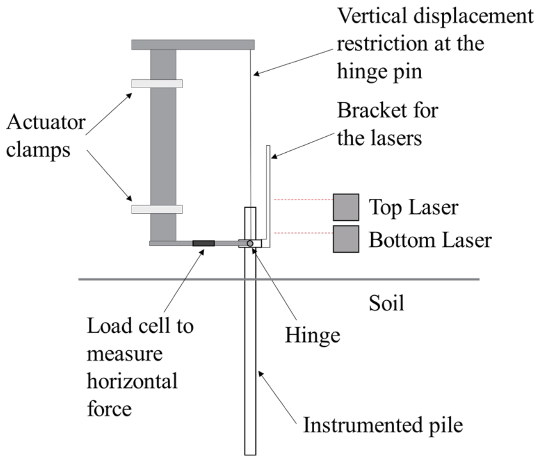

Fig. 1. Illustration of centrifuge setup.

The un-instrumented aluminium piles had an external diameter, wall thickness, and length (from the toe to the hinge) of 0.96 m, 32 mm and 21.6 m, respectively. The pile Young's modulus=68.9 GPa, giving a rigidity $EI$ = 770 MN.m$^2$. The piles instrumented with optic fibre and strain gauges are shown in Fig. 2.

The pile instrumented with 13 pairs of strain gauges had them spaced at 1.66 pile diameters ($d$) along its length. The scaled prototype external diameter and roughness (with epoxy) was 1.114 m and 35.6 μm, respectively.

Fig. 2. Aluminium piles of same dimensions instrumented with optic fibre (left) and strain gauges (right).

The pile instrumented with optic fibres had two strings of fibre placed diametrically opposite to each other, running along its length from 1*d* above the pile toe to roughly 1.5*d* below the pile hinge collar. The fibres were attached to the pile with an adhesive and covered with epoxy. The scaled prototype diameter and roughness (with epoxy) was 1.002 m and 16.0 µm, respectively. Differences in roughness between the piles could be due to the epoxy taking the shape of the strain gauges and cables on the pile.

### 2.2 Cantilever test to measure rigidity

Due to differences in external diameter, a cantilever test was performed to understand how the epoxy cover and instrumentation would affect the rigidity of the pile. The test was performed at a 1g station and involved fixing each pile on one end (top) and applying a point load on the other end (toe), while measuring the displacement. The load applied was measured using a load cell and the displacement was measured using a displacement transducer. Several loading and unloading cycles were performed to observe if hysteresis due to the epoxy was observed in the load displacement behaviour. The results of the cantilever tests are shown in Fig. 3.

It is evident that the epoxy required to cover the strain gauges and the cables increased the stiffness of the aluminium pile by about 15% (with EI = 889 MN.m$^2$), whereas for the optic fibre pile the effect was negligible. This change in stiffness impacts the pile head load-displacement behaviour, as well as the bending moment profiles.

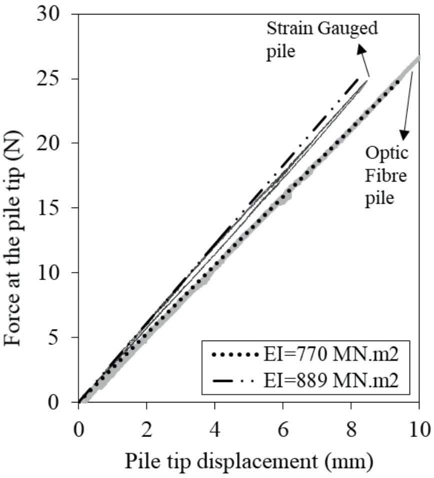

Fig. 3 Force vs displacement from cantilever test on strain gauged pile and optic fibre pile.

## 3 RESULTS AND DISCUSSION

Results from monotonic lateral push tests performed separately with the two piles are discussed in this section. During the test with the strain gauged pile, one of the sensors failed and so data corresponding to a depth of around 11 m below mudline was missing.

### 3.1 Bending moment profiles

Bending moment profiles for lateral displacements of 0.5*d* and 1.0*d* at the hinge level are shown in Figure 4. The bending moment profile for the strain gauged pile exhibits a larger peak for both displacement levels, which could be attributed to the increased stiffness due to the epoxy. The larger number of data points available from the optic fibre pile (77 in total) is evident, leading to a more continuous bending moment profile compared to the strain gauged pile (12 data points only). While more data points suggest that fitting a curve should be easier, the added noise needs to be smoothed to obtain realistic soil pressure profiles, as these are very sensitive to the BM fitted curve.

### 3.2 p-y curves

Figure 5 shows the p-y curves derived from the two piles, in terms of the mobilised pressure normalised by the undrained shear strength and pile diameter, for depths of 3.28m and 6.64m below mudline. Boundary conditions adopted for the integration were:

- Lateral displacement measured by the bottom laser; and
- Zero displacement at the depth of the zero crossing on the soil pressure profile, as suggested by Ilyas et al. (2004).

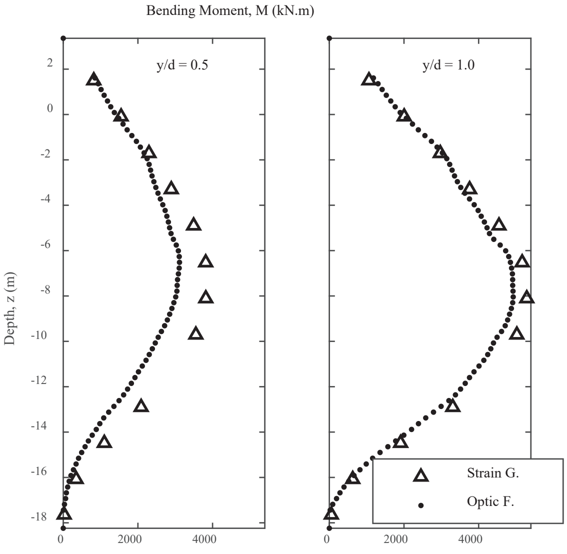

Fig. 4. Comparison of Bending moment profiles from pile instrumented with strain gauges and pile instrumented with optic fibre, at 0.5d and 1.0d pile head displacement.

It is observed from Figure 5 that the p-y curves from the piles instrumented with strain gauges and the p-y curves from the piles instrumented with optic fibre yield similar results. However, it is worth mentioning that due to the high sensitivity of the optic fibre sensors, some data points at very small displacements had to be removed due to excessive noise.

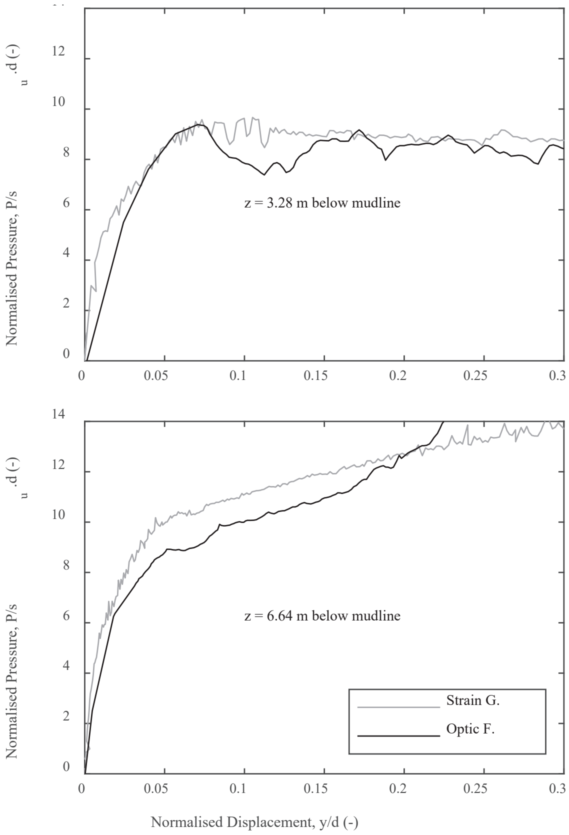

Fig. 5. p-y curves from strain gauged pile and optic fibre pile.

## 4 CONCLUSIONS

Results of a monotonic lateral push test performed with both strain gauges and optic fibre instrumented piles are presented and compared. Differences in head-load displacement and bending moment magnitude were observed and can be primarily attributed to the additional epoxy required to cover the strain gauges.

The bending moment profile from the optic fibre pile has over five times more data points than the strain gauged pile. However, the data tends to be noisy, and some smoothing is required in order to fit a curve to the bending moment profile, before double differentiating to obtain the soil pressure.

In this particular test, only one of the strain gauges failed, therefore, the interpretation of the data was relatively straight forward. However, if more strain gauges had failed, and at critical locations, the interpretation of the bending moment profiles could be severely impacted (as it would become difficult to fit a reasonable curve). In the case of the optic fibre pile, if one of the grating sensors were to fail, it would be less critical as the number of sensors is significantly higher.

Normalised p-y curves obtained with both systems yield similar results, however, at small displacements some data points collected with the optic fibre system had to be removed due to excessive noise, which impacted interpretation of the data. Future improvements to the processing of optic fibre data could explore more effective ways of filtering the noise, such as determining the minimum amount of data points needed to fit a curve to the bending moment profile.

## ACKNOWLEDGEMENTS

This work was supported by the ARC Industrial Transformation Research Hub for Offshore Floating Facilities which is funded by the Australian Research Council, Shell Australia, Woodside Energy, Bureau Veritas and Lloyds Register Group (IH140100012). The fourth author also acknowledges support from Shell Australia via the Shell Chair in Offshore Engineering at UWA.

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