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Setup and calibration of piles with FBG strain sensors in a geotechnical centrifuge

Configuration et calibration de pieux équipés de capteurs de deformation FBG dans une centrifugeuse géotechnique

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ABSTRACT: This paper discusses technical aspects of the experimental setup and calibration processing during centrifuge testing of single piles, instrumented with fibre Bragg grating (FBG) strain sensors, under vertical loads. Results illustrate the influence of the pile head connection method and data processing/correction of FBG readings. First, experimental data demonstrate issues encountered when adopting a rigid connection between a loading device, and how these can be tackled by adopting a point-to-surface contact. Second, the paper presents a method to minimise, in FBG strain sensor data, issues relating to pile bending during routine compression calibration and centrifuge testing.

RÉSUMÉ: Cet article aborde les aspects techniques de la configuration expérimentale et du traitement de la calibration lors des essais en centrifugeuse de pieux simples, instrumentés avec des capteurs de contrainte à réseaux de Bragg en fibre optique (FBG), sous des charges verticales. Les résultats illustrent l'influence de la méthode de connexion de la tête de pieu et du traitement/correction des données des capteurs FBG. Tout d'abord, les données expérimentales mettent en évidence les problèmes rencontrés lors de l'adoption d'une connexion rigide entre un dispositif de chargement, et comment ceux-ci peuvent être résolus en adoptant un contact ponctuel avec la surface. Ensuite, l'article présente une méthode pour minimiser, dans les données des capteurs de contrainte FBG, les problèmes liés à la flexion du pieu lors de la calibration de compression de routine et des essais en centrifugeuse.

Keywords: Centrifuge; pile; calibration; fibre Bragg grating (FBG).

1 INTRODUCTION

Geotechnical centrifuge testing is extensively used for modelling axial loading and force transfer mechanisms of piles in various scenarios, including external loading and during excavations. The configuration and calibration of model piles are crucial to ensure the reliability of the measured pile axial force.

Researchers have used a variety of methods to apply external loads to a pile head, such as fixing dead weights (Loganathan et al., 2000), or using mechanical load actuators (Song et al., 2022). The use of a rigid connection between the pile head and the load actuator components has advantages with respect to pile-load alignment and the ability to apply both driving and pulling forces to the pile. This method may, however, cause bending of the pile and/or experimental errors at the attached load cell.

FBG sensors can be used to measure strains/loads within structural elements in centrifuge tests (Li et al., 2020; Song et al., 2022). Song et al. (2022) incorporated embedded FBGs to measure pile axial force F_i using its positive correlation with FBG wavelength shift $\Delta\lambda_{B_i}$ at particular FBG strain sensors B_i (Figure 1(a)). FBG strain sensors are not affected by electrical noise and their size (diameter of 0.22 mm) makes them ideal for being glued inside hollow model piles for force measurement.

This paper presents data from a recent centrifuge modelling study concerning tunnel-pile interactions. The effect of two actuator-pile connection methods is examined first; an improved calibration method for FBG strain sensors placed inside model piles prior to and during centrifuge tests is proposed.

2 CENTRIFUGE TEST SETUP

Tests were conducted at 60 g within the 2 m radius, 50 g-tonne NCG centrifuge. Dry Leighton Buzzard Fraction E sand (0.14 mm average diameter, 1.58 uniformity coefficient, 2.65 specific gravity, 1.01/0.61 maximum/minimum void ratio, 90% relative density) and an eccentric rigid boundary mechanical tunnel model (90 mm diameter, 180 mm cover depth, 225 mm buried depth; Song et al., 2022) were adopted. The 60 g level was applied at half the tunnel's burial depth, i.e. 113 mm from the surface. The pile models, made of aluminium tube, have a 12.6 mm outer diameter (including a 0.3 mm thick layer of sand bonded to the shaft to get a rough shaft-soil interface), 9.3 mm inner diameter, and 150 mm length below the surface. Pile models were pushed vertically into the sand at 1 g using guides after the sand was prepared. The pile head load was applied by a stepper motor driven actuator during tests. FBGs were fixed on the smooth inner wall of the pile models using superglue (Figure 1). A "dummy pile" with similar specifications but with temperature sensors located inside was buried used to obtain data for temperature compensation of the FBGs.

The centrifuge test configuration represents a full-scale prototype scenario of 0.756 m diameter and 9 m deep piles located above/adjacent to a 5.4 m diameter tunnel with a 10.8 m cover depth.

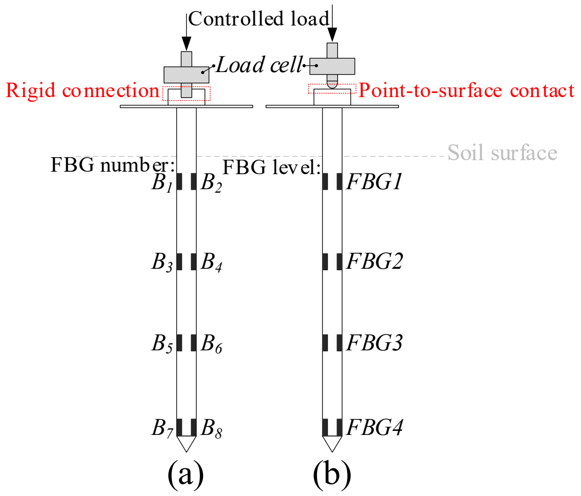

Figure 1. Diagrams of (a) rigid connection and (b) point-to-surface contact between load cell and pile head.

3 EXPERIMENTAL RESULTS

3.1 Influence of the connection at the pile head

Figure 1 illustrates the standard model piles, as well as the two types of connection methods between the pile head and the load cell above it: a "rigid connection", where the lower part of the load cell is threaded onto the pile head, and a "point-to-surface contact", where a hemispherical base of the lower part of the load cell makes contact with the top plane of the pile head. The upper end of both load cells is threaded to the loading device above, delivering only vertical force. Figure 2(a) shows the difference in pile axial forces for the two FBG sensors at each level (i.e. $\Delta F = F_i - F_{i+1}$, where i and $i+1$ refer to the FBGs on opposite faces, Figure 1(a)). The discrepancy in axial force serves as an indicator of the magnitude of pile bending.

The rigid connection increased the pile bending. In contrast, the point-to-surface contact reduced the force difference ΔF compared with the rigid connection. Whilst in theory using the average FBG readings of the two sensors on opposite faces should still provide an accurate measurement of axial force, this relies on precise positioning and alignment of the sensors, which is difficult to achieve in practice. Figure 2(b) shows that the point-to-surface contact tended to give higher FBG load readings (also described later).

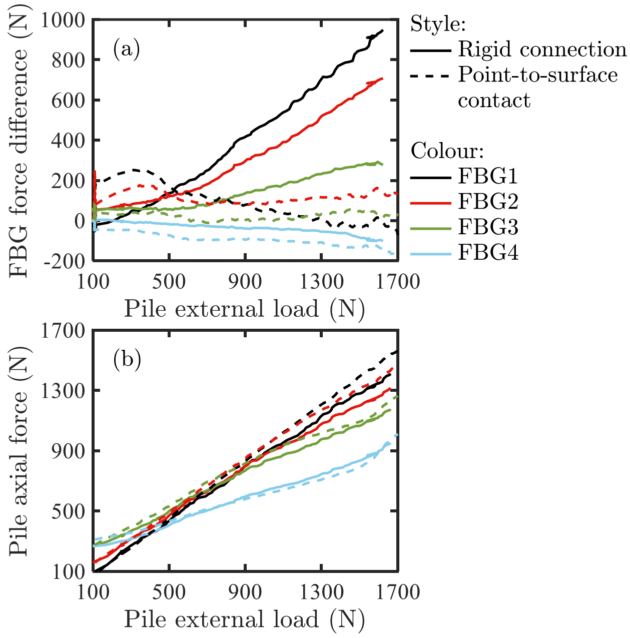

Figure 2. (a) FBG force difference between opposite positions at same level and (b) pile axial force with rigid connection and point-to-surface contact during loading.

3.2 FBG strain sensor calibration

In this paper, the axial force along the pile N_j is inferred from the average wavelength shift $\Delta\lambda_{FBG_j}$ of two FBGs at the same level (at FBG_j, Figure 1(b)) as:

$$N_j = K_{FBG_j}(\Delta\lambda_{FBG_j} - \Delta\lambda_{T_j}) + \Delta N_{exp} \quad (1)$$

where j is the FBG level reference number, K_{FBG_j} (in N/pm, pm=picometre) is FBG calibration coefficient,

$\Delta\lambda_{T_j} = K_t\,\Delta T$ is the temperature-induced wavelength offset proportional to the change in temperature ΔT by a factor $K_t = 32$-41 pm/°C estimated for no mechanical strains, and ΔN_{exp} is an offset introduced during centrifuge testing to correct for the disturbance resulting from the loading system. $\Delta\lambda_{T_j}$ and ΔN_{exp} are zero during K_{FBG_j} calibration tests performed at constant temperature.

3.2.1 Coefficient calibration

Table 1 shows the range, mean, and standard deviation (STD) of K_{FBG} from five sets of routine lab compression tests at 1 g within a standard loading frame (Lab C, two cycles from 0-600-0 N with an increment of ±100 N; a small cylindrical aluminium block with a conical groove matching the shape of the pile tip provides a surface for loading), two sets of compression tests using a loading/fixing system that fits on the centrifuge done at both at 1 g and 60 g (Cen 1 g, Cen 60 g, as above), and seven lab tension tests at 1 g (Lab T, from 0-200-0 N with an increment of ±20 N). After each cycle of loading-unloading, the position of the pile was altered through translation and/or rotation.

Table 1. FBG calibration coefficients from lab compression (C), centrifuge compression, and lab tension (T) tests.

		FBG1	FBG2	FBG3	FBG4
Lab C	K_{FBG}	2.5-2.6	2.5-2.6	2.5-2.6	2.4-2.6
	Mean	2.53	2.54	2.57	2.52
	STD	0.048	0.052	0.024	0.064
Cen 1 g	K_{FBG}	2.6-2.7	2.7-2.8	2.7-2.8	2.8-2.9
	Mean	2.63	2.74	2.71	2.83
	STD	0.016	0.043	0.043	0.090
Cen 60 g	K_{FBG}	~2.6	~2.7	2.6-2.7	2.7-2.8
	Mean	2.59	2.70	2.66	2.73
	STD	0.022	0.040	0.037	0.044
Lab T	K_{FBG}	2.3-3.0	2.5-2.7	2.5-2.8	/
	Mean	2.62	2.54	2.62	/
	STD	0.229	0.070	0.080	/

The deviation in 1-g lab compression coefficient K_{FBG} is likely caused by pile bending due to misalignment within the loading frame, despite attempts to reduce its effects. Overall, the values of lab compression coefficient K_{FBG} are stable and satisfactory, supported by the results of the centrifuge and tension tests discussed below.

Next, the centrifuge compression coefficient K_{FBG} under 1-g and 60-g levels are discussed. K_{FBG} at 60 g was slightly smaller (by ~2.1% on average) than the results obtained at 1 g (conducted prior to and after the 60 g tests, without adjusting any components), which implies a slight (and acceptable) overestimation of the pile axial force when using K_{FBG} from 1 g lab compression tests.

To minimise the effect of pile bending on K_{FBG}, lab tension tests were performed. The pile was fixed at the top and weights were hung from the pile via a clamp that was attached to the pile base, close to FBG4 (thus, FBG4 readings are unreliable). Neglecting the outliers for FBG1, $K_{FBG_{1-3}}$ are consistent with the compression results.

3.2.2 Offset at elevated gravity

The tunnel-pile interaction tests included "stabilisation cycles" in which the centrifuge was repeatedly spun up/down to achieve a more uniform stress distribution within the soil and at soil-structure interfaces, and ensuring consistency between tests (Song et al., 2022).

To minimise deviations in FBG readings due to misalignments and bending, $\Delta N_{exp} = \Delta N_{exp,1} + \Delta N_{exp,2}$ in Eq. (1) is estimated for each test in two steps: (i) $\Delta N_{exp,1}$ is estimated during the stabilisation cycles of a specific centrifuge test as the difference between the readings of FBG1 at 15 mm beneath the surface and the theoretical axial load at the surface (neglecting the shaft friction between FBG1 and the soil surface); next, (ii) $\Delta N_{exp,2}$ is a constant for the instrumented pile estimated at a given g-level in centrifuge calibration tests without soil to account for the (minor) effects of the self-weight of FBG sensors and the glue covering them when g-level is increased.

Figure 3 illustrates the uncorrected changes in pile axial forces (when $\Delta N_{exp} = 0$) in two centrifuge tests during stabilisation cycles from 1-60-10-60-10-60 g. Two scenarios are included: subplot (a) for a pile positioned directly above the tunnel; subplot (b) for a pile located 150 mm away from the tunnel centreline ("no tunnel"). The pile axial forces showed good repeatability subsequent to the first spin-up to 60 g. Specifically, in Figure 3(a)-(b), the axial force at FBG1 was 15/-30 N at the 1st 10 g, whereas it was 2/-60 N for the subsequent 2nd and 3rd 10 g.

In these tests, the "theoretical surface load" (i.e. theoretical pile load at the soil surface) is equal to 22 N and 110 N at 10 g and 60 g respectively: e.g. at 60 g it consists of 105 N from the self-weight of the components above the soil surface (adjusted for distance from centre of rotation of the centrifuge) and a constant load of 5 N applied by the stepper motor (controlled load in Figure 1).

The FBG correction of $\Delta N_{exp,1} = 20$ N and 82 N were estimated, respectively, at the last spin-down to 10 g in Figure 3(a)-(b), so that the FBG1 load matched the theoretical surface load of 22 N. Note that $\Delta N_{exp,1}$

estimated for FBG1 is applied to all other FBG loads while considering $\Delta N_{exp,2} = 0$.

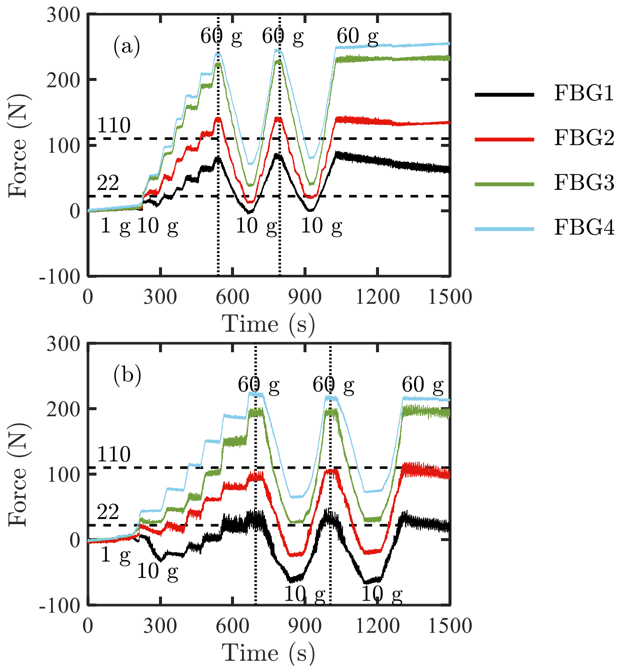

Figure 3. Changes in pile axial forces during centrifuge spin up/down for pile (a) above tunnel and (b) no tunnel.

Next, $\Delta N_{exp,2}$ is added to measurments at the end of the spin-up (or stabilisation cycles) once the final target 60 g is reached. This second offset $\Delta N_{exp,2}$ was estimated, at each FBG location, from the difference between the measured average pile axial forces and the theoretical pile self-weight in two calibration centrifuge tests at N-g without soil (while assuming $\Delta N_{exp,1} = 0$); as shown in Figure 4, $\Delta N_{exp,2}$ is within the range of 1-33 N, which is relatively small compared with the pile load capacity measured in centrifuge tests at 60 g (~1.6 kN, including base load and shaft friction).

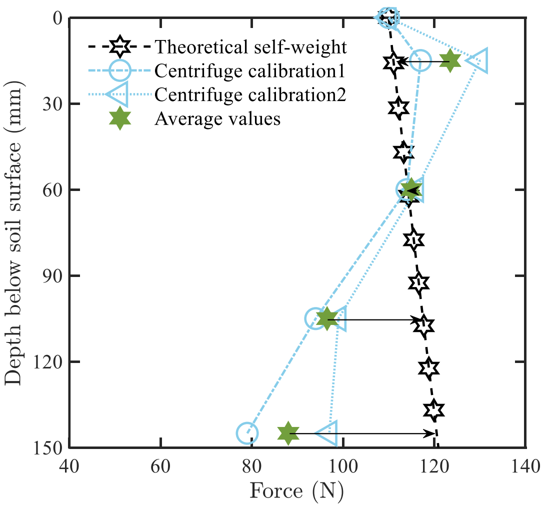

Figure 4. Pile axial force offset at 60 g

4 CONCLUSIONS

This paper summarised some "lessons learned" from recent centrifuge testing of FBG-instrumented model piles under vertical loads at the University of Nottingham Centre for Geomechanics (NCG). The following main conclusions can be drawn.

(1) The point-to-surface contact between the load actuator and pile head reduced errors in measurement of axial forces with respect to a rigid actuator-pile connection, as point-to-surface contact minimises pile bending from the misalignment between the load actuator and model pile.

(2) A systematic FBG calibration method for measuring pile axial force was applied: i) determine the calibration coefficient K_{FBG} between the axial force along pile centreline and the average wavelength shifts of two FBG strain sensors on opposite sides at the same pile level; ii) assign the theoretical load values to easily evaluated FBG positions at a stable small g-level before reaching the target gravity as a reference for correcting all pile axial forces; iii) correct the pile axial force again at the target gravity based on the deviation between the measured pile axial force in the absence of soil and the theoretical axial force from the pile self-weight. This method effectively reduces the effects of pile bending, soil movement, superglue and FBG self-weight, and other potential sources of error in the data processing.

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