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Application of Fibre Bragg Grating sensor in mini pile performance and behavior monitoring

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ABSTRACT: Fibre Bragg grating (FBG) sensor technology has been recognised as a reliable strain sensing system in geotechnical engineering due to its certain advantages over traditional electrical resistance strain gauges. However, the uses of FBG sensors in geotechnical applications are still limited. This paper demonstrates an application of FBG sensors for measuring axial strain in a driven mini pile. Installation and calibration methods, and data interpretation of FBG sensors are discussed. After calibration, mini pile was instrumented with FBG sensors and driven into a medium to dense sand deposit using a high-frequency hand-held jackhammer, followed by a quick pull-out pile load test. The results confirm the viability of FBG sensors in measuring stress developed along pile's shaft and demonstrates the robustness of FBG in withstanding the high frequency of pile installation. Distribution of axial strains along the pile shaft was found to be similar to reported patterns in the literature.

1 INTRODUCTION

Fibre optic sensing system is getting wide attention in civil engineering applications due to its variety of benefits such as high accuracy, small size, resistance to corrosion, capability of multiplexing and immunity to electromagnetic interference (Glisic and Inaudi, 2008). Fibre optic sensors have been used in a number of geotechnical applications including monitoring of tunnel linings, embankment settlement and slope stabilisation (Zhu et al., 2009; Cheung et al., 2010; Zhu et al., 2017). Among all fibre optic sensing technologies, Fibre Bragg Grating (FBG) is considered as the most popular technique for strain measurement. There exists very few studies that applied FBG sensors in performance monitoring of driven concrete piles, bored piles and jacked piles (Lee et al., 2004; Liu and Zhang, 2012; Schilder et al., 2012; Liu et al., 2017). The FBG sensors were usually mounted on the reinforcement bars of concrete piles such that they were well protected inside the piles. However, study on the performance of FBGs in monitoring driven steel pile is more limited (Doherty et al., 2015).

Previous studies show that FBG sensor have pronounced strain measuring performance in steel driven pile. Doherty et al. (2015) has conducted a lateral load test on an instrumented test steel driven pile to investigate the robustness of FBG sensors in measuring strain and its ability to withstand high impact pile driving. It was reported that the FBG sensors survived from the driving process. The bending moment inferred from the FBG strain output also well matched the measured moment at field. The tested pile has a relative large diameter of 340 mm and was driven under high impact accelerations. There is concern on the robustness of FBG sensors when installed on small diameter piles, which are driven under high impact frequency. FBG sensing technique is yet to be adopted under AS 2159-2009, hence research is required to investigate the feasibility of using FBG for pile monitoring. This study aims to assess the survivability of FBG sensors when subjected to high frequency pile driving forces where other technologies are found to be not feasible. The installed pile was then monitored by FBGs to measure the distribution of axial strains along a mini driven pile under static pull-out loading.

2 FIBRE OPTIC SENSING SYSTEM

Fibre Bragg Grating (FBG) sensors have been considered as an alternative strain measurement technique with high sensitivity to the strain applied. Bragg grating is engraved on an optic fibre string, which reflects a narrow-spectrum light at a specific wavelength, called Bragg wavelength (Morey et al., 1990). The strain measurement technique utilises the nature of Bragg grating in which a shift of Bragg wavelength occurs when the fibre is subjected to physical elongation. The change of strain can then be determined by measuring the Bragg wavelength shift with a FBG interrogator, which analyses optical spectrum received from optic fibres. It should be noted that temperature change can also induce shift of Bragg wavelength. Since quick pile load test was planned for this study, the change of temperature under ground surface during monitoring stage was limited and hence the effect of temperature was omitted.

2.1 *Strain monitoring using strain gauges*

Preliminary tests on using conventional electrical resistance strain gauges to measure change of strain of small diameter steel pipe were conducted. After cutting the mini pile into multiple sections along the pile shaft, the strain gauges were bonded on the inner surface of the pipe and protected with adhesive. The cut sections were then welded together to form the one-piece mini pile. During field installation, it was found that the strain gauges did not survive due to the high frequency impact driving and harsh soil condition. Multiple cables within the pipe makes the driving process complicated, increasing the chance of failure. More importantly, to protect strain gauges' cable inside the pile, a bottom cap needed to be used which changed the response of the pile during loading. Previous attempts of installing the gauges on cut grooves on surface of mini piles were also found unsuccessful. Adopting FBG sensor for measuring strain of steel driven pile has the following advantages over conventional electrical resistance strain gauges.

- Multiple sensors in one fibre means that the number of alternative strain gauge cables need to be handled is largely reduced;
- Thorough cleaning procedure, which is important for strain gauges, is not required for optic fibre that implies quicker installation time;
- More likely to survive from the high-level vibration induced by the jackhammer; and
- Minimal noise since there is no electrical excitation.
- Larger number of strain measurement on one single fibre providing more accurate strain distribution along the mini pile shaft.

3 FIELD TEST PROGRAM

3.1 *Test description*

A pull-out test was conducted on a 1.6 m long instrumented driven steel mini pile in a medium to dense silty sand test site according to FHWA (2005), ASTM-D1143 (2013) and D3689 (2013) with some modifications. The mini pile in this research has an outer diameter of 42.4 mm with wall thickness of 2.6 mm. The pile was instrumented with three FBG strings, with six sensors on each string (270 mm spacing). The strings were arranged concentrically around the pile's central axis, so the angle between them is 120^o.

3.2 *Site description*

The test site was located at a Melbourne's southern suburb, Fingal in Victoria, Australia. A series of in-situ geotechnical tests were conducted down to a depth of 10 m, including five Cone Penetration Tests (CPT) and three Standard Penetration Tests (SPT) within and around the test area. Detailed analysis of the site's subsurface conditions was reported by Mehdizadeh et al. (2018). The *in-situ* investigation and test results indicate that the site consisted of organic fill in the top 400 mm underlain by silty sand deposit. No water table was encountered at the site down to 10 m depth. Interpretation of the geotechnical investigation suggests that the friction angle of Fingal sand increases from 32^o at 1 m depth to 38^o at 2 m depth with an average unit weight of 17 $kN/m^{3.}$

3.2.1 *FBG packaging*

A common approach to attach FBG strings in con-crete pile is embedding them in the reinforcement bars by machining a narrow groove on its surface. FBG strings are placed in the grooves and covered with adhesive for protection (Hong et al., 2016). In a similar approach three 4 mm wide and 1.5 mm deep grooves, namely, G1, G2 and G3, were machined along mini pile's shaft, separated by 120^o. A space of 200 mm was left at the top of test pile so that there is enough space for jackhammer for pile driving.

Optic fibre string with six FBG sensors written was placed in each groove and was protected with adhesive. Fig. 1 shows the layout of FBG sensors along the test pile's surface. The FBG sensors have spacing of 270 mm to obtain enough data point for strain profile development. In this study, there was a total of 18 FBG sensors mounted on the mini pile for monitoring the strain developed during pull-out load test.

3.3 *FBG calibration for strain measurement*

This study utilised a simple supported beam test for FBG calibration. A FBG sensor monitoring system is composed of an optical spectrum analyser (OSA), a broadband light source and an optical fibre with etched FBG. In typical measuring process, there is a shift of Bragg wavelength due to applied strain and this shift was detected by the OSA. Fig. 2 shows a schematic drawing of a typical FBG sensor system. In such system, a circulator is required to transmit the incoming light to the fibre and redirect the reflected spectrum to OSA. This technique shows high accuracy in detecting wavelength of laser sources in wavelength meters for many years (Zhu et al., 2017).

3.3.1 *Laboratory set-up*

Simply supported beam tests with mid-point load were performed on the instrumented mini pile as shown in Fig. 3 to calibrate the FBG sensors before performing the field load tests. In the calibration pro-cess, mid-point loads were applied in various stages: 0, 5, 10, 10 (unload), 15 and 0 kg (unload). At each stage, the reflected spectrum was recorded with OSA. The spectrum recorded at 0 kg loading is considered as the initial state which acts as a reference spectrum to determine the shift of Bragg wavelength due to each loading.

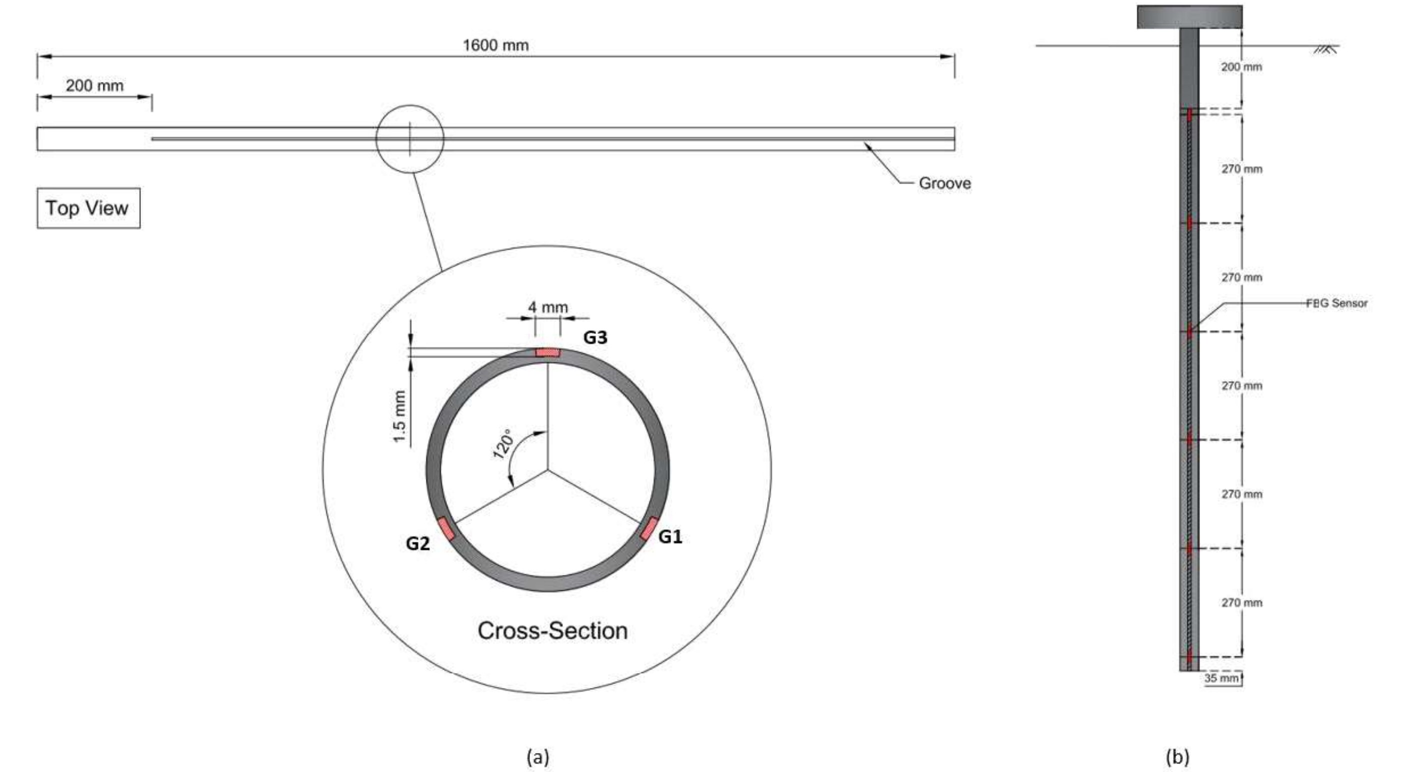

Figure 1. Dimension of grooves along test pile's shaft and layout of FBG sensors inside the pile: (a) dimensions of the cross section of test pile and configuration of grooves; (b) layout of FBG sensors along test pile's surface.

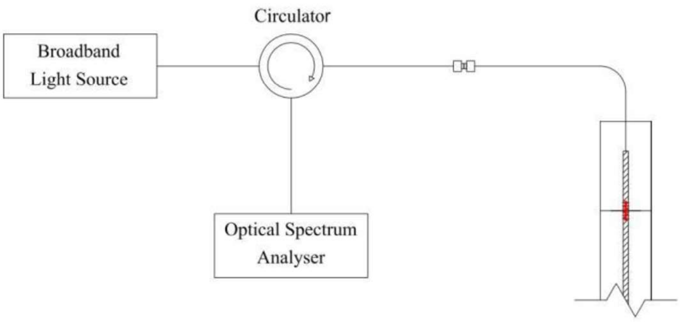

Figure 2. A schematic of FBG sensor system.

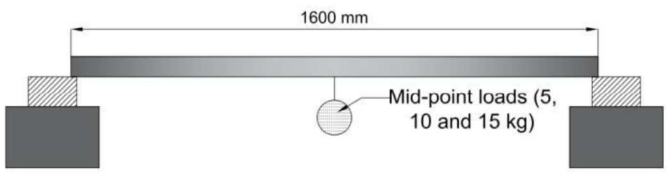

Figure 3. Schematic drawing of FBG calibration set-up.

3.3.2 *Post-processing of FBG spectrum*

To use FBG effectively in strain measurement, it is important to accurately estimate the peak wavelength of FBG spectrum and hence, an appropriate peak-tracking technique is required (Tosi, 2017). One of the common peak-tracking techniques is curve fitting method which interpolates the measured spectrum with an analytical function including spline, polynomial and Gaussian (Lee et al., 2007; Bodendorfer et al., 2009; De Sousa et al., 2011; Chen and Vallan, 2015). In this study, the Gaussian fit algorithm proposed by Lee et al. (2007) is adopted to estimate the peak wavelength. This algorithm is implemented in MATLAB to interpret the collected spectrums. Utilising mechanics theory with known pile properties, the theoretical strain at each FBG sensor during each loading stage can be calculated. The theoretical strains were plotted against the corresponding shifts of Bragg wavelength. Fig. 4 illustrates an example calibration result for one of the optic fibre strings, G1.

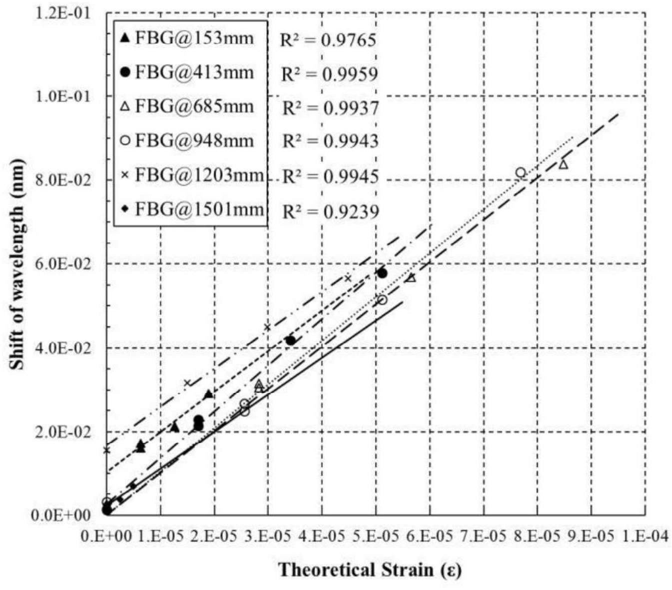

Figure 4. Linear correlation between theoretical strain and shift of Bragg wavelength (nm).

The correlation between theoretical strain and shift of wavelength lies on a linear regression line which suggests reliability of system in load and unload strain measurement. The linear relationship can then be used to determine the strain developed in field load test.

3.4 *Static quick pile load test*

The instrumented mini pile was driven vertically an embedment depth of 1.4 m and tested under static pull-out loading. Fig. 5 illustrates the static load test set-up. Two 100 mm by 100 mm timber pads were used as reaction for the applied loads. To eliminate the impact of organic material on the test result, a 400 mm trench was dug and the test pile was installed at the bottom of the trench. The pile was subject to pull-out load with an incremental load of 0.5 kN until failure occurred. Each incremental load was maintained for 5 mins. Deformation was recorded using two digital indicators mounted on the pile top cap. Failure was defined such that the pile can no longer sustain the applied load and continuous jacking was required. The pile was unloaded to 0 kN at the end of the test and residual settlement recorded.

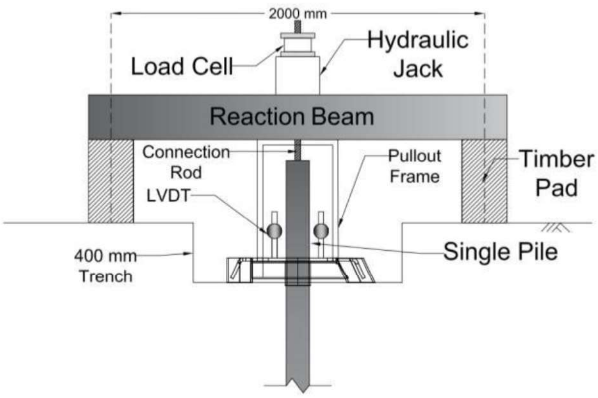

Figure 5. Static load test set-up at Fingal, Melbourne

3.4.1 *FBG spectrum acquisition*

The FBG sensor system used to acquire FBG spectrum in field is illustrated in Fig. 6. After the instrumented pile was driven into ground, an initial FBG spectrum was recorded for each optic fibre string along the groove to represent the reference spectrum (initial reading). During the static load test, the spectrum of each string at each incremental load was recorded such that there were three spectrums collected at each load.

4 RESULTS AND DISCUSSION

4.1 *Pile load test result*

The ultimate pull-out capacity of the mini pile was back-calculated using Fuller and Hoy (1970), De Beer (1972) and GCP-18 (2015) methods.

Figure 6. Photograph of FBG sensing system: OSA (left) and Broadband light source (right).

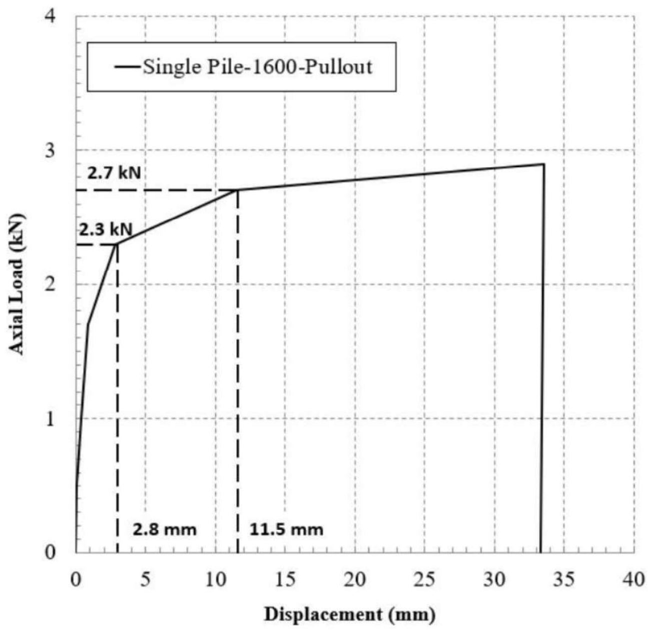

Figure 7. Load-settlement curve for pull-out load test on single vertical pipe pile.

By performing analyses using these approaches, it was identified that De Beer (1972)'s approach better determines the pullout capacity of this driven mini pile. Fig. 7 shows load-settlement curve of the static pull-out load test conducted on the single vertical pile. The pull-out capacity of the single vertical pile was found to be 2.3kN. The displacement has increased significantly from 2.8 mm to 11.5 mm when load in-creased from 2.3 kN to 2.7 kN. This behaviour will be discussed in later section.

4.2 *FBG results*

The FBG spectrums obtained during static load test were analysed using the same approach as mentioned in section Post-processing of FBG spectrum. With the linear regression line of each FBG sensor, the shift of Bragg wavelength was converted to strain. In order to obtain the strain profile of the entire pile, the strain of all FBG strings were averaged. Fig. 8 illustrates the average strain of the pile during pull-out loading.

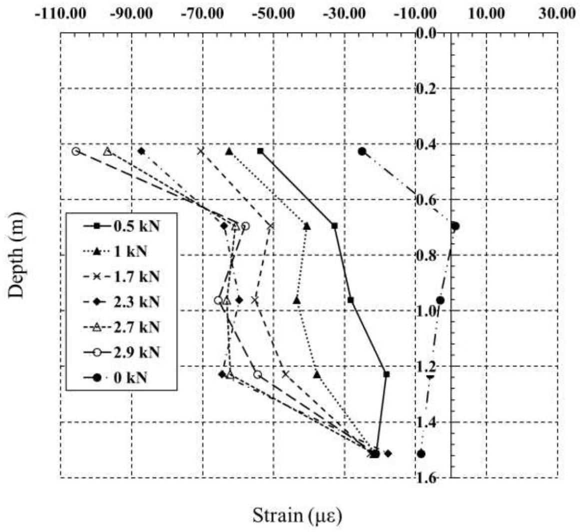

Figure 8. Average strain profile of test pile at different load stages based on FBG strain measurement.

The negative strain represents the tensile strain profile of the pile. It can be observed that the strain profile is consistent with the typical change in strain in vertical pile subjected to pull-out load. The strain at pile top is the highest and decreases with depth. It can also be seen that the strain of the test pile increases with increasing loading. This shows the reliability of using FBG sensor to monitor pile's behaviour. The strain at the bottom FBG was 21 με at all load stages as the last FBG array was located at 35 mm above the pile toe, which explains why the strain was not zero.

Gao et al. (2017) has conducted compressive model load test on a cast-in-place large-diameter pile (PCC pile) and the strain developed was monitored by FBG sensors. The model PCC piles were hollow concrete tube which have diameter of 200 mm and 315 mm with embedment depth of 1.4 m. FBG strings were mounted in 2 mm grooves at the inner and outer wall of the piles. Fig. 9 shows the strain profile along the outer wall of the PCC pile. Their study showed a similar profile as the measured strain profile in the single pile load test conducted in this study.

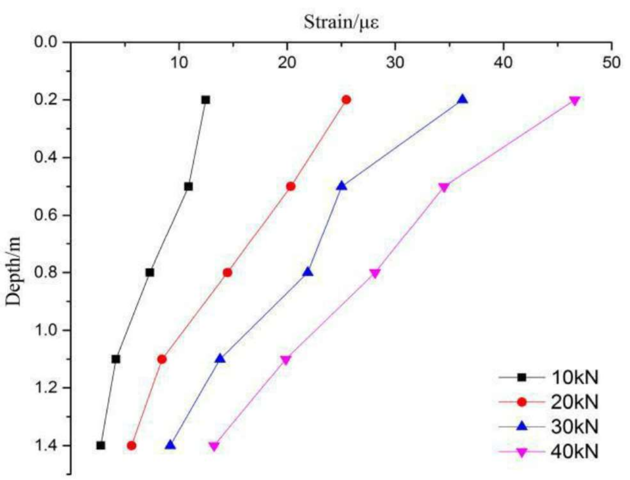

Figure 9. Strain profile along the outer wall of the model PCC pile (Gao et al., 2017).

It should be noted that, from Fig. 8, the strain has decreased from 2.7 kN load stage. This indicates that the skin friction along pile shaft has reduced significantly from this point onward. As mentioned in section FBG results, there was a dramatic increase of displacement when load was increased to 2.7 kN. This is suspect that the soil has failed from this loading which can be backed up by the FBG strain measurement. At the top of the pile, the strain at 2.9 kN was higher than the strain at 2.7 kN which was because the pile top was above ground surface at these loads and the axial strain were not affected by surrounding soil. The re-sult of FBG shows consistency with load-settlement curve, which indicates the feasibility of using FBG in pile monitoring.

5 CONCLUSION

This study has summarised a field pile load test to assess the robustness of FBG sensors in mini driven pile monitoring application. The distribution of axial strains along a driven mini pile under pull-out loading was also investigated. A steel pile was instrumented with three FBG strings and driven to medium to dense silty sand deposit using high frequency jackhammer. A pull-out load test was conducted, and the pile behaviour was observed through FBG sensors.

The research outcomes and recommendations are summarised below:

- The FBG strings survived from high frequency driving where traditional strain gauges didn't.
- The calibration results show that the correlation between theoretical strain and shift of wavelength lies on a linear regression line which is good to determine strain occurred in field test.
- The pull-out capacity of a single vertical pile, installed in a sandy material, was 2.3 kN based on De Beer (1972)'s method.
- FBG results showed reasonable match with the strain profile obtained from other literature which also use FBG as measurement technique.
- FBG sensor system seems to be a feasible technique for mini pile monitoring.

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