Fibre Bragg grating sensor: A powerful technique for monitoring soil and driven mini piles interaction

Chin Fung Tsang[1], A. Mehdizadeh[1], and M.M. Disfani[1]

[1] Department of Infrastructure Engineering, Melbourne School of Engineering, The University of Melbourne, Melbourne, Australia.

ABSTRACT

In recent years, fibre Bragg grating (FBG) sensor, as a relatively new strain sensing technology, is gaining wide attention in monitoring the response of geotechnical structures. FBG sensors have been used in a variety of geotechnical structures monitoring but its application in small-sized driven piles remains unknown due to limited field studies. This paper reports the feasibility of using FBG sensor strings to measure axial strains in steel driven mini piles. The effect of batter configuration on capacity of driven mini piles in a medium to dense sand deposit based on strain measured from FBG sensors is also discussed. A steel, open-end mini pile was instrumented with FBG strings for strain monitoring. Same instrumented pile was reused for both vertical and battered pull-out load tests. For battered case, the mini pile was driven at an angle of 25° from the vertical axis. The strain profile measured from FBG sensors showed that load capacity of battered mini pile consists of not only skin friction but also lateral soil resistance. The FBG packaging method adopted in this study was also proven to be a robust approach for multiple testing, which significantly increase the efficiency of strain monitoring for small-sized geo-structures.

Keywords: pile instrumentation; fibre bragg grating sensors; soil/pile interaction; battered pile

1 INTRODUCTION

Accurate and reliable measurement of strain profile is an essential part of geotechnical structure monitoring. This enables early warning of geohazards, and investigation of soil-structure interaction which helps the development of design methods for geotechnical structures (Zhu et al., 2017). Traditional strain sensors include electric strain gauges, extensometers and dial gauges. In recent year, fibre optic sensor is gaining wide attention in geotechnical monitoring due to its large numbers of advantages in comparison with traditional sensors including high accuracy, light weight, ease of installation, resistance to corrosion, capability of multiplexing and immunity to electromagnetic interference (Morey et al., 1990; Ferdinand et al., 1997; Glisic and Inaudi, 2008; Yin et al., 2008).

Among all fibre optic sensing techniques, Fibre Bragg Grating (FBG) is the most common technique for strain measurement (Hong et al., 2016). FBG technique offers discrete strain measurement over long distances. Each Bragg grating is engraved with UV light on an optic fibre string, which functions as a special reflector reflecting a narrow-spectrum light at a specific wavelength when there is physical elongation happening on the fibre. If there are multiple FBGs in one fibre string, multiplexing process is required to ensure each FBG reflects a unique wavelength such that the overlap of wavelength along a single fibre can be avoided. The most utilized approach for this purpose is wavelength division multiplexing (WDM) (Zhu et al., 2017).

Over the past years, FBG sensors have been successfully implemented in a variety of geotechnical applications in field, which includes the performance monitoring of slopes (Dou and Li, 2013), soil nails (Zhu et al., 2007) and piles (Lee et al., 2004; Liu and Zhang, 2012; Doherty et al., 2015). For field instrumented tests, various packaging techniques have been developed to protect the FBG sensors from harsh environment. Existing packaging techniques include encapsulating FBGs in container or groove and protected with adhesive (Zhou et al., 2003), packaging FBGs in steel tube (Schilder et al., 2012) and in Fibre Reinforced Polymer (FRP) (Tremblay et al., 2009). These techniques allow FBG sensors to survive from harsh soil environment but they, on the other hand, increase the size of FBGs to the size of traditional strain sensors. Consequently, the stress and strain fields of soils in the field tests are likely to be disturbed. The impact of large-sized FBG sensor can be significant when testing small-scaled geotechnical structures in field. In recent years, researchers have embedded bare FBGs in grooves and covered with adhesive to measure strain on soil nails (Li et al., 2013a; Li et al., 2013b). This approach can minimize the disturbance of soil but its robustness in strain measurement for small-sized driven piles is still unknown due to limitation of field studies (Doherty et al., 2015; Zhang et al., 2018).

2 BATTERED DRIVEN MINI PILE

Small-sized piles are usually adopted when traditional shallow and deep foundations are not feasible at a location where access for equipment is limited, such as mountainous areas (Thompson et al., 2010; Kyung and Lee, 2017). Small-sized piles, such as micropiles and mini piles can be installed in a batter configuration. Previous studies investigated the effect of batter configuration on the load capacity of small-sized piles (Tsukada et al., 2006; Sharma et al., 2014; Kyung et al., 2016). However, most studies mainly focused on the effect of changing batter angle on the pile load capacity, without monitoring of soil-pile interaction. The lack of understanding of soil-pile interaction can reduce the robustness of designs of battered piles (Lin et al., 2014). Moreover, there is still lack of field measurement to compare the strain profiles of vertical and battered mini piles developed when subjected to pull-out load.

In this study, the interaction between soil and mini driven pile was monitored using FBG sensors to assess the effect of batter configuration on mini pile interaction with soil when subjected to vertical pull-out load. This research also aimed to confirm the robustness of using FBG sensors in strain monitoring for small-sized geo-structure.

3 SITE DESCRIPTION

Instrumented static load tests were performed at Fingal; Victoria, Australia. To characterize the test site, three Cone Penetration Tests (CPT) were conducted within test area. A dense layer of silty sand was encountered at a depth of 2.5 m. The in-situ tests indicate that the site consisted of organic fill in the top 400 mm underlain by silty sand deposit. Water table was not observed down to the bottom of deepest borehole (10 m). Soil unit weight and modulus of elasticity are back-calculated based on the CPTs results according to Guide to cone penetration testing (Robertson and Cabal, 2010; Mehdizadeh et al., 2018). The variation of these parameters with soil depth are presented in Table 1.

Table 1. Key soil parameters at the test site.

Depth (mm)	q_c (MPa)	γ (kN/m^3)	E_s (MPa)
0 - 500	1.5	16.8	9
500 - 1000	3	16.3	11
1000 – 1500	3.3	16.9	15
1500 – 2000	5.3	17.6	24
2000 - 3000	14.6	18.7	52

q_c = cone resistance, γ = soil unit weight; E_s = modulus of elasticity

4 TEST PILES INSTRUMENTATION

The test piles are 1.6 m long steel, open-ended pipe piles with an outer diameter of 42.4 mm and a wall thickness of 2.6 mm. Three grooves, namely G1, G2 and G3, 4 mm wide and 1.5 mm deep were machined along each test pile shaft (Fig. 1a) to mount FBG sensors. The layout of FBG sensors on the battered mini piles are shown in Fig. 1b, which has the same layout as the vertical mini pile. A groove is required as a two-part adhesive could be applied to cover the groove for harsh environment protection (Fig. 2) without affecting the outer shape of pipes. The grooves were arranged concentrically around the pile's central axis, so the angle between them is 120°. A 200 mm space was left at pile top such that there is enough room for jackhammer for pile driving. A fibre string with a total of six FBG sensors was embedded in each groove. Locations of the six sensors were 200, 470, 740, 1010, 1280, 1550 mm away from the pile head.

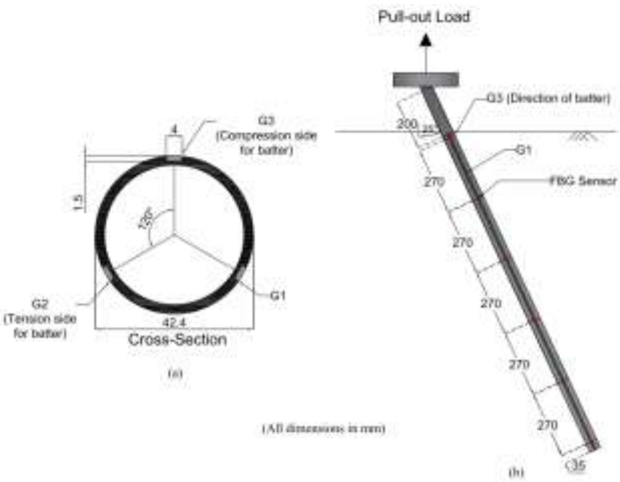

Fig. 1. Dimension of grooves along test pile's shaft and layout of FBG sensors inside the pile: (a) Cross-section of pile and configuration of grooves; (b) layout of FBG sensors along battered mini pile length.

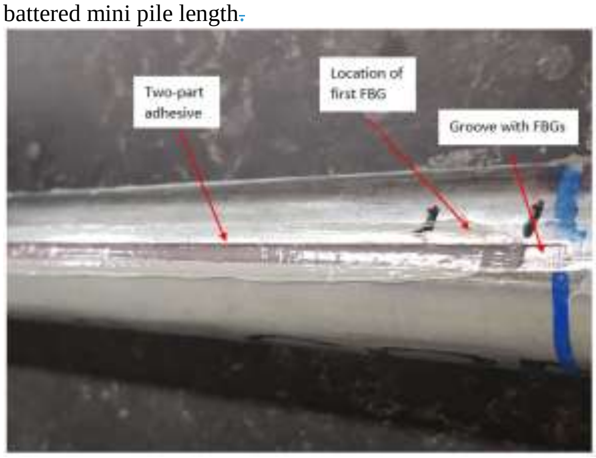

Fig. 2. Two-part adhesive for harsh environment protection.

5 FIELD TEST PROGRAM

The test program aims to assess the feasibility of using FBG sensors in field and the effect of batter configuration in interaction of battered mini pile with surrounding soil. Pull-out load tests were conducted on single vertical and battered mini piles. For battered pile load test, the instrumented mini pile was driven into the ground at an angle of 25° from vertical with a hand-held jackhammer. The embedment depths for both vertical and battered piles were 1400 mm. The behavior of these mini piles under pull-out load was monitored according to FHWA (2005), with some modifications. The impact of the top 400 mm organic fill was eliminated by installing the piles in a 400 mm excavated trench. The piles were subjected to an incremental load of 0.5 kN, with each load step maintained for 5 minutes until failure. Continuous jacking to keep the applied load constant was considered as the failure criteria as it indicated that pile cannot sustain the applied load. Strain along the pile length was measured with FBG sensors 5 minutes after each load step. When setting up the test, the FBG string along G1 was broken due to technical issue and hence, strain was not recorded for this particular string.

6 TEST RESULTS AND DISCUSSION

In this field test regime, same pipe was used for both vertical and battered load tests. The pipe was pulled out in axial direction after the first test (vertical case) without residual bending. It was observed that this packaging method was a robust approach to protect FBGs for multiple tests, which highly increased the efficiency and reduced the installation time for mini pile monitoring. Although the fibre string was protected in the grooves with adhesive, the strings that come out from the grooves at 200 mm depth were left unprotected. It should be noted that the string along G1 was broken due to this unprotected joint which should not be considered as an issue associated with FBG technique in general. As fibre is fragile under bending, every section of the fibre should be well protected to survive from possible damage and surrounding environment. As the strings were allowed to be mounted along the pipe's surface due to small-sized and lightweight fibre string, hence the surrounding soil was not disturbed due to use of FBG, and actual soil-pile interaction can be monitored. This cannot be achieved by traditional electrical strain gauge based on authors' experience.

To assess the effect of batter configuration on mini pile, the strain profiles along the length of vertical and battered mini piles were compared. The strain measurement obtained from the FBG sensors along G2 and G3 for vertical and battered pile load tests are analyzed. For battered case, the strain along G2 represented the tension side, while the strain along G3 represented the compression side. Both vertical and battered mini piles showed the same ultimate load of 2.3 kN. Altough it is excpeted the battered case would provide a higehr load capacity, the measured performance was lower than expected which can be attributed to soil non-uniformity. Only the strain

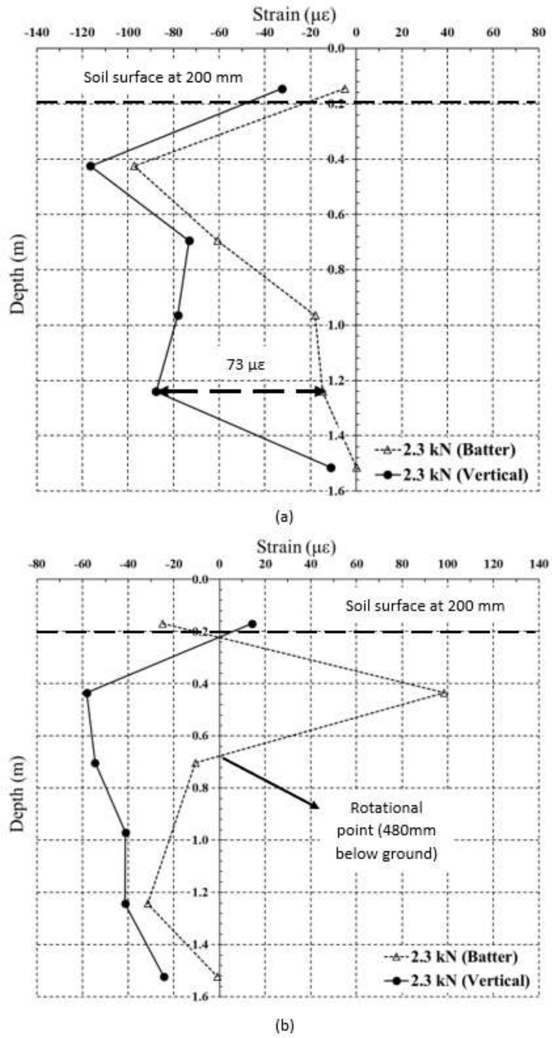

Fig. 3. Comparison of strain profiles along the length of vertical and battered mini piles: (a) G2; and (b) G3.

developed at ultimate load is reported as shown in Fig. 3. From Fig. 3a, it can be observed that, for both vertical and battered cases, the strain along the pile length in G2 showed tensile behavior, in which the strain has increased down to depth of 435 mm and decreased after this point. It should be noted that the tensile strain in vertical case is higher than the battered case by 73 με or 83% at depth of 1040 mm below ground, which indicates the load capacity of battered mini pile not only consists of skin friction, but also other resistance component. When a battered pile is subjected to vertical pull-out load, the load can be decomposed into axial and lateral loads. In axial and lateral conditions, the dominant resistances are considered to be skin friction and lateral soil resistance respectively (Mehdizadeh et al., 2016; Kyung and Lee, 2017). Prasad and Chari (1999) suggested that the pile is subjected to compressive lateral soil pressure along the direction of batter until it reaches a point of rotation. The pile is then subjected to soil pressure from opposite direction, which causes tensile strain along the pile length. This soil-pile interaction is confirmed by the strain measurement along G3 (direction of batter). It can be seen from Fig. 3b that the measured strain profile of vertical case agrees with the trend of typical vertical pile in which the strain has decreased with depth. It should be noted that the measurement showed that the strains along G2 was about the strains along G3, which could be due to eccentric loading. In practice, the tensile strain of the vertical case should be assessed by averaging the strain measured in all grooves to obtain a reliable measurement. In battered case, there is increase of compressive strain to depth of 235 mm below ground and decreased from this point onward. A point of rotation was observed at 480 mm below ground. Tensile strain was developed along G3 from this point. The results confirmed the model suggested by Prasad and Chari (1999) and provides reliable information for development of robust design method for battered mini piles.

7 CONCLUSIONS

The effect of batter configuration on mini piles under vertical pull-out load was investigated. For this purpose, quick pile pull-out load tests were conducted on vertical and battered mini piles in sandy soil. An open-ended steel mini pile was instrumented with FBG sensors to monitor soil-pile interaction. The robustness of using FBGs in small-sized geo-structures monitoring was also discussed. The strain measurement along pile length showed that there is a rotational point observed at 235 mm below ground. The tensile strain developed in vertical case at 1040 mm below ground was 83 percent higher than the one in battered case, which indicates that load capacity of battered mini pile consists of not only skin friction but also lateral soil resistance. The FBG packaging method adopted in this study was shown to be a robust approach for multiple testing, which significantly increases the efficiency of strain monitoring for small-sized geo-structures.

8 ACKNOWLEDGEMENTS

This project was funded by the Australian Research Council (ARC) Linkage scheme – LP160100828. The authors acknowledge the financial and technical support from our industry partner, Surefoot Pandoe Pty Ltd. Camilo Pineda, senior structural engineer at Surefoot is acknowledged for his contribution.

9 REFERENCES

Doherty, P., Igoe, D., Murphy, G., Gavin, K., Preston, J., McAvoy, C., Byrne, B., Mcadam, R., Burd, H. & Houlsby, G. 2015. Field validation of fibre Bragg grating sensors for measuring strain on driven steel piles.

Dou, Z. & Li, H. 2013. The slop disaster early warning system of fiber Bragg grating anchor bar sensor based on RFID. Appl. Math. Inform.

Ferdinand, P., Magne, S., Dewynter-Marty, V., Martinez, C., Rougeault, S. & Bugaud, M. Applications of Bragg grating sensors in Europe. Optical Fiber Sensors, 1997. Optical Society of America, OTuB1.

FHWA 2005. Micropile design and construction. US Department of Transportation, Federal Highway Administration, Washington, DC, Report No. FHWA-NHI-05-039.

Glisic, B. & Inaudi, D. 2008. Fibre optic methods for structural health monitoring: John Wiley & Sons.

Hong, C.-Y., Zhang, Y.-F., Zhang, M.-X., Leung, L. M. G. & Liu, L.-Q. 2016. Application of FBG sensors for geotechnical health monitoring, a review of sensor design, implementation methods and packaging techniques. Sensors and Actuators A: Physical, 244(184-197.

Kyung, D., Kim, D., Kim, G. & Lee, J. 2016. Vertical load-carrying behavior and design models for micropiles considering foundation configuration conditions. Canadian Geotechnical Journal, 54(2).

Kyung, D. & Lee, J. 2017. Uplift Load-Carrying Capacity of Single and Group Micropiles Installed with Inclined Conditions. Journal of Geotechnical and Geoenvironmental Engineering, 04017031.

Lee, W., Lee, W.-J., Lee, S.-B. & Salgado, R. 2004. Measurement of pile load transfer using the Fiber Bragg Grating sensor system. Canadian geotechnical journal, 41(6), pp 1222-1232.

Li, G.-W., Hong, C.-Y., Dai, J., Yu, L. & Zhou, W.-H. 2013a. FBG-based creep analysis of GFRP materials embedded in concrete. Mathematical Problems in Engineering, 2013(

Li, G.-w., Pei, H.-F. & Hong, C.-y. 2013b. Study on the stress relaxation behavior of large diameter B-GFRP bars using FBG sensing technology. International Journal of Distributed Sensor Networks.

Lin, H., Ni, L., Suleiman, M. T. & Raich, A. 2014. Interaction between laterally loaded pile and surrounding soil. Journal of geotechnical and geoenvironmental engineering, 141(4), pp 04014119.

Liu, J. & Zhang, M. 2012. Measurement of residual force locked in open-ended pipe pile using FBG-based sensors. Electron. J. Geotech.

Mehdizadeh, A., Disfani, M., Evans, R., Gad, E., Escobar, A. & Jennings, W. 2016. Static Load Testing of Concrete Free Reticulated Micropiles System.

Mehdizadeh, A., Disfani, M., Tsang, C., Narsilio, G., Evans, R. & Gad, E. 2018. Performance of a new driven battered micropiles system in sand. DFI-EFFC International Conference on Deep Foundations and Ground Improvement. Italy.

Morey, W. W., Meltz, G. & Glenn, W. H. Fiber optic Bragg grating sensors. Fiber Optic and Laser Sensors VII, 1990. International Society for Optics and Photonics, 98-108.

Prasad, Y. V. & Chari, T. 1999. Lateral capacity of model rigid piles in cohesionless soils. Soils and Foundations, 39(2), pp 21-29.

Robertson, P. K. & Cabal, K. 2010. Guide to cone penetration testing for geotechnical engineering. Gregg Drilling & Testing.

Schilder, C., Kohlhoff, H., Hofmann, D. & Habel, W. Structure-integrated fibre-optic strain wave sensor for pile testing and monitoring of reinforced concrete piles. Proceedings of the 6th European workshop on structural health monitoring.

Sharma, B., Zaheer, S. & Hussain, Z. Experimental Model for Studying the Performance of Vertical and Batter Micropiles. Geo-Congress 2014: Geo-characterization and Modeling for Sustainability, 2014.

Thompson, F., Salisbury, N., Khattak, A., Hastings, A. & Foster, M. 2010. Integration of Optimum, High Voltage Transmission Line Foundations. Electrical Transmission and Substation Structures 2009: Technology for the Next Generation.

Tremblay, J., El-Gamal, S., Wattanasanticharoen, E. & Benmokrane, B. Reinforced concrete pile load testing with fiber optic sensor. 4th International Conference on Structural Health Monitoring of Intelligent Infrastructure, SHMII 2009, 2009.

Tsukada, Y., Miura, K., Tsubokawa, Y., Otani, Y. & You, G.-L. 2006. Mechanism of bearing capacity of spread footings reinforced with micropiles. Soils and foundations, 46(3), pp 367-376.

Yin, J., Zhu, H., Fung, K., Jin, W., Mak, L. & Kuo, K. Innovative optical fiber sensors for monitoring displacement of geotechnical structures. Proceedings of the HKIE Geotechnical Division 28th Annual Seminar, Hong Kong, 2008. 287-294.

Zhang, C.-C., Zhu, H.-H., Chen, D.-D., Xu, X.-Y., Shi, B. & Chen, X.-P. 2018. Feasibility Study of Anchored Fiber-Optic Strain-Sensing Arrays for Monitoring Soil Deformation beneath Model Foundation. Geotechnical Testing Journal, 42(4), pp.

Zhou, Z., Graver, T. W., Hsu, L. & Ou, J.-p. 2003. Techniques of advanced FBG sensors: Fabrication, demodulation, encapsulation, and their application in the structural health monitoring of bridges. Pacific Science Review, 5(1), pp 116-121.

Zhu, H.-H., Shi, B. & Zhang, C.-C. 2017. FBG-Based Monitoring of Geohazards: Current Status and Trends. Sensors, 17(3), pp 452.

Zhu, H.-H., Yin, J.-h., Jin, W. & Zhou, W.-H. Soil nail monitoring using Fiber Bragg Grating sensors during pullout tests. The Joint 60th Canadian Geotechnical and 8th IAH-CNC Conferences. Ottawa:[sn], 2007. 821-828.