

Innovative Geotechnical Design, Smart Construction and Optic Fibre Sensing

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ABSTRACT

The future of built infrastructure including geotechnical structures relies on smarter use of information to make better engineering decisions leading to a reduction in risk, costs and carbon footprint and enhanced resilience and integrity. The rich information obtained from emerging sensor technologies can act as a catalyst for innovative geotechnical design, smarter construction planning and more cost-effective and energy efficient construction processes. Design of geotechnical structures requires consideration of risks associated with variable geology, which can be managed by having high spatial resolution data to understand the effects of varying soil-structure interaction. At present, there is a mismatch between the data needed and what current sensing systems can collect, which makes data-driven decision hard to achieve in real-time. Fibre optic sensing (FOS) is capable of obtaining high spatial resolution data in geotechnical engineering projects, allowing real-time acquisition of large volumes of data that can be analysed and fed back to designers and constructors to improve construction performance. This paper presents a review of the role of data in driving smart, cost-effective and energy-efficient design and construction and in particular discusses how optic fibre sensing can facilitate this in geotechnical engineering projects. Three local case studies are presented to demonstrate the capability of fibre optic monitoring. The first case describes the use of FOS in developing a full picture of soil-structure interaction on driven mini-piles during pile load tests, enabling the development of new analytical solutions for this footing system. The second case presents monitoring of a pipe-jacking project in Melbourne where a Glass-fibre Reinforced Plastic pipe was instrumented with FOS to capture its behaviour during the drive. The measured longitudinal and circumferential strains led to better understanding of the effects of the process on the pipes, providing a foundation for design improvement. The third case demonstrates the capability of FOS in long-term monitoring of elastic and permanent deformations in pavements constructed with recovered waste tyres.

Keywords: geotechnical field instrumentation, fibre optic sensing, soil-structure interaction, data-driven design

1 INTRODUCTION

In recent years, sensing technology research has undergone a revolution, especially in the built infrastructure environment. Effective use of monitoring systems can provide essential information for innovative design and effective use of new materials (Soga and Schooling 2016). There are numerous conventional geotechnical monitoring systems adopted over the years to monitor geo-structures at discrete locations, such as vibrating wire strain gauges to measure one dimensional strain (Tedd et al. 1984), inclinometers and tiltmeters to measure relative deflection and bending moments (Clark & Richards, 2005) and automated total stations to measure 3D displacements (Beth et al. 2003). However, a major drawback of these monitoring tools is their discrete nature leaving large areas of structures un-monitored and as a result, relevant structural behaviours or defects cannot be captured (Lienhart et al. 2018). Further, as these instruments are influenced by various external factors such as humidity, temperature and depth (Mikkelsen 2003), a feasible, cost effective and robust monitoring system is needed to tackle the challenges faced by currently available monitoring systems.

Fibre optic sensing (FOS) has emerged as a strong, robust and accurate sensing technology (Soga and Schooling 2016) with the capacity to provide site-scale mechanical and thermal monitoring for applications which require continuous measurement, high spatial resolution of sensing, or span over long distances. Innovations and usages of fibre optic sensors in “structural health monitoring” of structures have been

increasing because of the advantages that fibre optic sensors provide (Huybrechts et al. 2016). In geotechnical structure monitoring, critical aspects such as fibre-soil interaction and fibre adhesion to the structures needs to be carefully considered since these factors can have a significant impact on the strain transfer efficiency from soil to fibre optic sensors and hence the structure (Zhang et al. 2020).

This study provides a summary of three unique local case studies conducted in Australia to demonstrate the capability of fibre optic monitoring in improving designs and facilitating the use of new material for geotechnical engineering.

2 SENSING TECHNIQUE

2.1 Fibre Bragg grating

Fibre Bragg grating (FBG) is a quasi-distributed sensor solution. The sensors are typically deployed along the length of an optical fibre. In this technique, the ultraviolet laser’s interference pattern is used so that the periodic structure of FBG can be generated (Meltz et al. 1989). When an incident spectrum of light propagates through the grating, as shown in Figure 1 one of the wavelengths called Bragg wavelength turns back while the remaining spectrum is not affected. When external axial strain takes place along the fibre, the FBG will respond accordingly, resulting in a proportional shift in the reflected Bragg wavelength. This shift can be converted to an equivalent strain through a one-time instrument calibration. The biggest advantage of FBG technology is that multiple measurement points can be set along one optical fibre

to create an array of independent sensors, thereby enabling efficient multiplexing and distributed measurement. Also, these multiplexed FBG sensors can be applied to monitor other parameters, such as strain and temperature in real time (FBG Principle 2020).

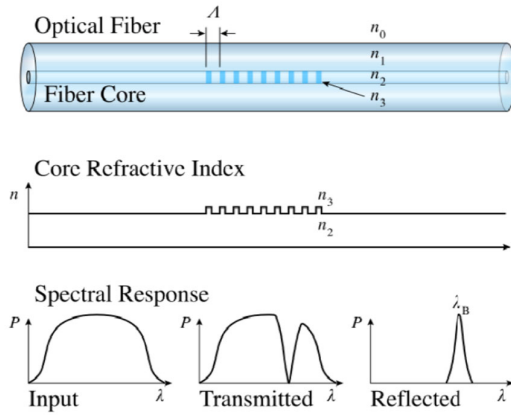


Figure 1. FBG Sensors Operating Principle (Rao 1998)

2.2 Installation methodology

A bare optical fibre is fragile and might not survive in harsh field conditions (Hong and Zhang 2016). Therefore, secure packaging techniques should be adopted. In the projects described in this study, the fibre optic cables were mounted onto the structures using a two-part epoxy adhesive. This adhesive requires 12 to 15 minutes curing time to achieve 20.7 to 27.6 MPa tensile strength. For the fibre packaged with adhesive, it is vital to consider the impact on strain transfer from the structure to embedded arrays (Zhang et al. 2020). In practice, a strain transfer efficiency factor should be applied, and this parameter can be obtained through laboratory or field calibration tests.

3 CASE STUDIES

Three local monitoring projects around Australia are presented. These projects utilised FBG sensors as the principal instrumentation technique to enhance our understanding of soil-structure interaction effects. The first case study describes the use of FOS in developing a full picture of soil-structure interaction on driven mini-piles during pile load testing, enabling the verification of analytical solutions for this footing system. The second case study presents some results from a pipe-jacked Glass-fibre Reinforced Plastic (GFRP) pipe monitored using FOS to assess its performance during the drive. The measured longitudinal and circumferential strains revealed the deformation pattern of GFRP pipe at each stage of the jacking process, which led to a better understanding of the process. The third case study demonstrates the capability of FOS in long-term monitoring of elastic and permanent deformations in pavements made with recovered waste tyres.

4 CASE STUDY 1: DRIVEN MINI-PILE

4.1 Project description

Field pile load tests were performed on mini-piles instrumented with fibre optic sensors to understand the degree of interaction with the surrounding soil. The test site is located in Fingal, Victoria, Australia. Three Cone Penetration Tests (CPT) were conducted within the test area. Figure 2 shows the results of the CPTs. Two CPTs were terminated at a depth of approximately 2.5 m, where a relatively dense layer of silty sand was encountered. The soil profile primarily consists of medium dense silty sand and the soil profile is consistent up to a depth of 2 m. No groundwater was encountered up to 10 m depth.

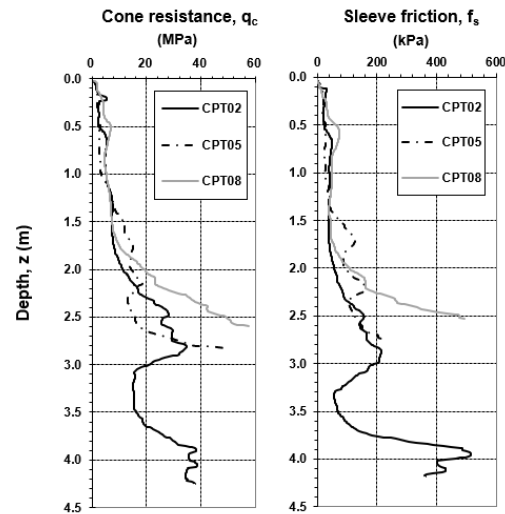


Figure 2. Results of CPTs performed at the test site (Tsang et al. 2019)

4.2 Monitoring motivation and purpose

Vertically loaded battered (raked) piles are used in various geotechnical applications, such as slope stabilisation, earth retention and bridge abutments. Most published studies describe the load response of battered mini-piles in model pile load tests (Tsukada et al. 2006, Kyung and Lee 2017). There are few studies reported that address fully instrumented field load tests to monitor the behaviour of battered mini-piles. The aim of this study was to understand the soil-pile interaction of a battered driven mini-pile by monitoring the strain development along pile's shaft during field load tests.

4.3 Instrumentation

The test mini pile is a steel, open-ended pipe pile 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 (Figure 3a) to mount FBG sensors. A fibre string with a total of six FBG sensors was embedded in each groove. Locations of the six sensors are provided in Figure 3b.

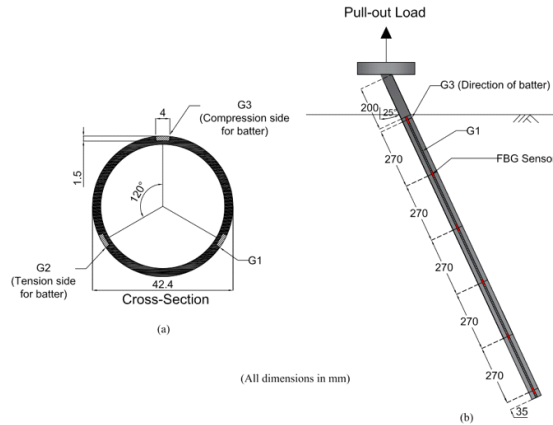


Figure 3. Dimension of grooves along test pile's shaft and layout of FBG sensors inside the pile: (a) Cross-section of pile and configuration of grooves; (b) layout of FBG sensors along battered mini pile length (Tsang et al. 2020a).

4.4 Results and analysis

Figure 4 shows measured strains in the fibres along the pile shaft. It can be seen that there exists a point of rotation when the battered pile was subjected to predominantly vertical load as indicated by the development of tensile strains measured along G3.

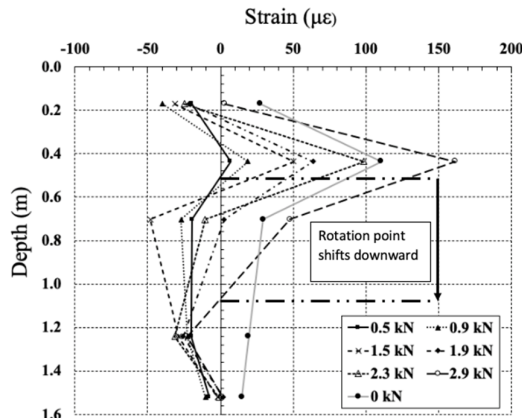


Figure 4. An example of measured strain curves along G3 during pull-out load stage (Tsang et al. 2019).

The measured point of rotation along the pile length (i.e. point where strain changed from positive to negative) shifted from 330 mm to 890 mm below ground surface with increasing load magnitude. Prasad and Chari (1999) has proposed Equation (1) to calculate the depth of point of rotation (a in metres) when a pile is subjected to ultimate lateral load.

$$a = \frac{-(0.567L + 2.7e) + (5.307L^2 + 7.29e^2 + 10.541eL)^{0.5}}{2.1996} \quad (1)$$

where e (m) is eccentricity of loading; and L (m) is embedment depth of pile. The measured depth of rotation point was then compared with the calculated value. The calculated value was 970 mm which shows good agreement with the measured value with a difference of 80 mm, or 5%. These preliminary FBG measurements show the shift of rotation point as load level increases, which helps determining the pile soil interaction at service load rather than just ultimate

load. This project proved the feasibility of using FBG sensors in mini pile monitoring, which also highlights the importance of conducting field monitoring when developing analytical solutions.

5 CASE STUDY 2: PIPE-JACKING

5.1 Project description

A GFRP pipe section was instrumented with fibre optic sensors to assess its field performance during the pipe-jacking process. This project comprised installation of a new sewer main pipe, approximately 1160 m in length. The instrumented section of sewer was launched from shaft KAL-10, at an invert depth of approx. 12.4 m with groundwater level of 11.5 m below ground level. Figure 5 indicates the pipeline alignment for the 580 m section of drive from shaft KAL-10 to KAL-11. Data was collected over discrete periods, commencing 100 m from shaft KAL-10.

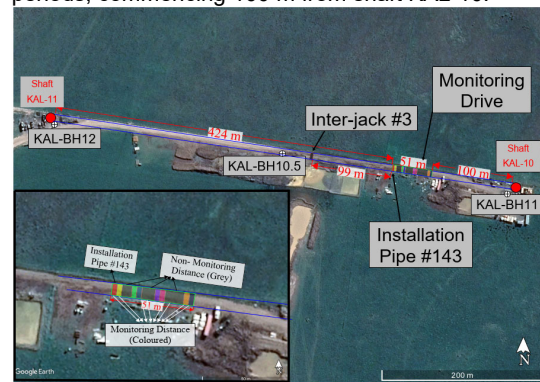


Figure 5. Pipe alignment and monitoring plan view (Tsang et al. 2020b)

5.2 Monitoring motivation and purpose

GFRP pipes have several benefits over traditional reinforced concrete pipes including greater tolerance to changes in direction and flexure, as well as higher compressive strength which reduces pipe thickness. However, previous investigations of this material were limited to controlled laboratory studies, and there is a lack of data to assess its field behaviour in construction (Robinson 2016). The aim of the study was to monitor and analyse the deformation and structural performance of a single GFRP pipe section during the jacking process taking into account the complexity of field conditions and the pipe-jacking process.

5.3 Instrumentation

In this project, twenty-four metres of field monitoring data was obtained from a 51 m length of drive. The instrumented GFRP pipe (number #143) was 3 m in length, 1.6 m inner diameter and 1.72 m outer diameter. The instrumentation involved 24 monitoring locations, comprising five FBGs at intervals along three circumferential cables,

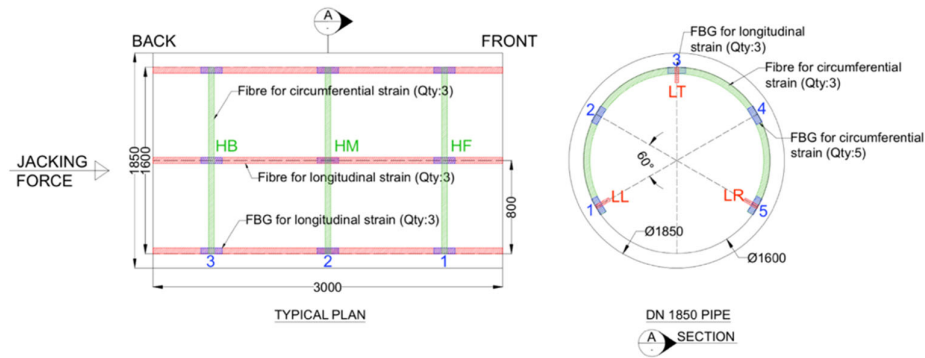


Figure 6. FBG sensor configuration (a) plan view and (b) cross-section view (dimensions in mm) (Jiang et al. 2019)

and three FBGs along three longitudinal cables attached to the intrados of the GFRP pipe as shown in Figure 6. For referencing purpose, the circumferential (or hoop strain) FBGs (with green hatch) were named Hoop Front (HF), Hoop Middle (HM), Hoop Back (HB) in the drive direction. In each circumferential array, the FBGs were numbered 1 to 5, clockwise from knee to knee, again viewing in the direction of the drive.

5.4 Results and analysis

The hoop strains measured from the HF (front array) and HM (middle array) fibres are analysed and

compared as shown in Figure 7. The strain at positions 1 and 2 are compared as an example of strain development during the jacking process. Significant patterns include first, HF1 experiences relatively higher compressive strain during the entire field monitoring period compared to HF2. Second, HM2 remains in compression which is the same as the behaviour of HF ring. Third, HM1 is the only FBG that experiences tensile strain, which is opposite to the behaviour observed at HF ring. Figure 8 shows the relative radial strains around the instrumented pipe at HF and HM arrays respectively.

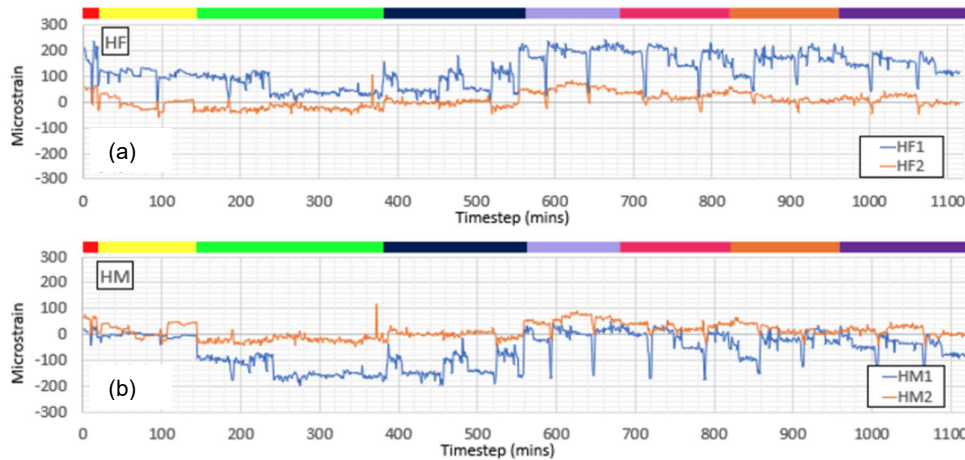


Figure 7. An example of measured strains around the circumferences of the pipe at: (a) HF (front ring), HF1 vs HF2 and (b) HM (middle ring), HM1 vs HM2 (Tsang et al. 2020b)

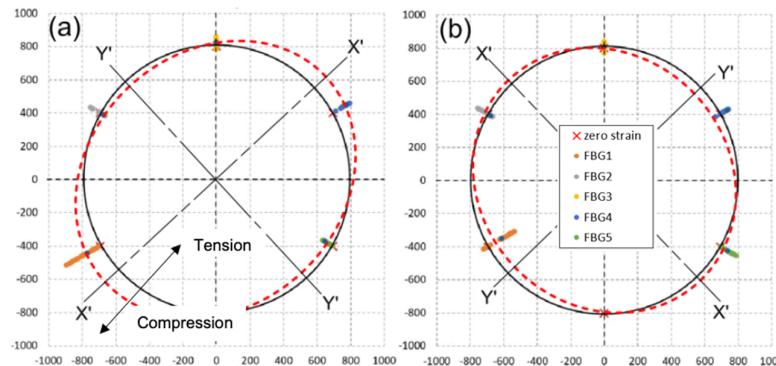


Figure 8. An example of radial strain development from measured hoop strain at chainage 143, 144, 147 and 148: (a) HF; and (b) HM (Tsang et al. 2020b)

By plotting the incremental hoops strains at the position of each FBG sensor, Figure 8 shows the development of hoop strains over the jacking period. A snapshot of the pipe distortion pattern at a specific time increment is represented by the dashed red line. In this case, Figure 8 a & b shows the distortion pattern 45 minutes after initial driving of pipe #144 (i.e. the pipe behind the instrumented pipe). From Figure 8, it can also be observed that there is an opposing structural behaviour between HF and HM arrays, which are only 1 m apart, indicating non-axis-symmetric 3D distortion along the pipe. This is inferred to be due to the effects of variable ground-structure interactions such as soil friction, soil contact area, slurry fluid lubrication and jack loading pattern.

6 CASE STUDY 3: PERMEABLE PAVEMENT

6.1 Project description

A full-scale waste-tyre based permeable pavement trial site was constructed and monitored at a carpark located at St Marys Park, City of Mitcham, South Australia. Figure 9 shows the typical cross section of the waste tyre-based permeable pavement used in this project.

While three different mixtures with varying tyre-derived aggregate (TDA) content, i.e. 30%, 40%, and 50%, were used as the surface layer to study their mechanical performance, the underlying layers, i.e. screening, subgrade, and geosynthetics reinforcement, had the same mechanical properties and configuration throughout the monitored area.

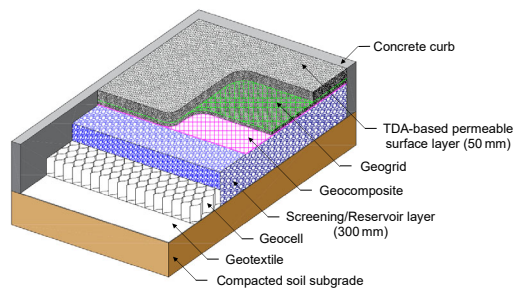


Figure 9. Typical cross-section of the pavement (Raeesi et al. 2020)

6.2 Monitoring motivation and purpose

In this application the objective was to observe how the “waste tyre permeable pavement”, developed at Melbourne School of Engineering, performed under real field conditions with traffic load and environmental loads both present. Because the exact location of a car tyre in a parking spot is hard to predict, multiple sensors with high spatial resolution were required to be able to capture any possible loading condition; hence optic fibre technology was used in place of hundreds of strain gauge sensors.

6.3 Instrumentation

In this project, two arrays of optic fibre were installed at each of the three instrumented carpark bays: one, with seven FBGs, located at the depth of two thirds of

the thickness of the surface layer, and the other array, with five FBGs, located on the top of the screening layer as shown in Figure 10.

In both cases, the optic fibre was mounted on a thin metal strip. To assure that the recorded shift in the wavelength was transformed to strain by the correct ratio, a strain gauge was installed next to one of FBGs on the strip.

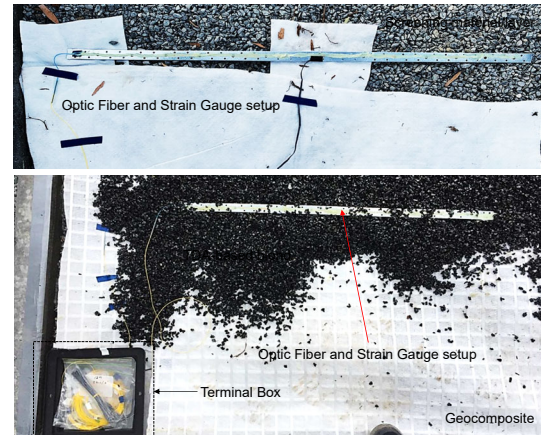


Figure 10. Installation of instruments for monitoring

6.4 Results and analysis

Figure 11 shows an example of the measured strain profiles at different depths. It can be observed that the peak strain reduces as the depth increases, which is in agreement with the stress-strain distribution in layered semi-finite systems. The measurements indicate that a decrease in the TDA content results in decrease in strains developed in both surface and screening layers.

The ratio of the peak strain measured at the interface to that measured in the surface layer is 29%, 18% and 11% for sections with 30%, 40%, and 50% TDA, respectively. This shows that ratio of the surface-to-bottom layer moduli should be decreasing as the TDA content increases. Considering the fact that the only changing factor between the monitored sections is the TDA content in the surface layer, it can be concluded that the modulus of the surface layer significantly increases, as the TDA content decreases from 50% to 30%. This was also verified by the results of other tests done at the carpark.

7 CONCLUSIONS

Three field performance monitoring projects of geotechnical structures using FOS technology are presented and discussed in this study. It is shown that FOS allows collection of data which cannot be easily obtained by conventional sensing techniques, especially for projects in harsh environments. This study provides some examples of data collected with fibre optic strain monitoring system in each project. The finding in each field monitoring scheme is summarised below:

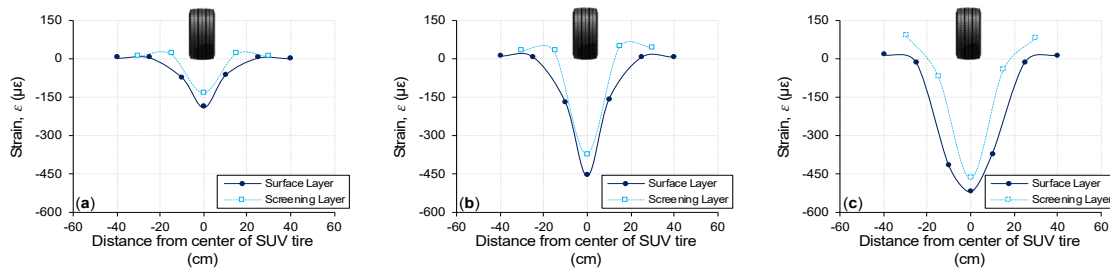


Figure 11. Strains measured at sections with a) 30%, b) 40%, & c) 50% TDA in the surface (Raeesi et al. 2020)

1. Mini driven pile: the soil-pile interaction of a battered mini pile was investigated, focusing on the strain development during field pile load testing. The measured strain curve matches the theoretical point of rotation which provides essential information for analytical solution development for service conditions.
2. Pipe-jacking: A GFRP pipe section was instrumented to study its field behaviour during pipe-jacking process. The data shows that a non-uniform diametric deformation occurs during jacking. The compression and tensile strains on the pipe intrados show that the pipe is subjected to inclined ovalisations which vary with longitudinal position along the pipe. This is a factor which is not considered in pipe-jacking design. The collected data allows assessment of the field performance of this relatively new pipe material, as well as providing data required for improved construction control.
3. Permeable pavement: A waste-tyre based permeable pavement was instrumented to assess the strain generated in layers with various tyre content. The FOS system was proved to work well in the aggressive pavement environment where humidity is typically high. Results indicate that the strain generated decreased with decreasing TDA content.

8 ACKNOWLEDGEMENTS

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