Smart slope monitoring through the use of fibre optic sensors

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ABSTRACT: This study demonstrates the use of fibre optic instrumentation such as an Optical Time-Domain Reflectometer as well as Fibre Bragg Grating sensors on a small-scale physical 1-g model to monitor potential slope movement. The scope is to improve current knowledge in the field of slope monitoring through the implementation of optic fibre sensors. Single-mode and multi-mode hetero-core optic fibre displacement sensors were created and directly embedded into layers of coarse-grained soil. By inducing critical slope conditions in the small-scale model through the course of several experiments we were able to identify localised failure zones and quantify signal attenuation. Using a calibrated source, it was possible to indirectly estimate microstrain and investigate spatial resolution of the sensing cable. Laboratory testing of the sensors and the sensing system allowed for further development of sensor integration techniques.

1 INTRODUCTION

The stability of natural or manmade slopes is still an open area for research although there has been progress over the last few decades. There is, however, still a need for slope monitoring and early-warning system development to reduce the risks associated with slope failure.

Slope failures usually occur quickly with little or no visual warning and according to Soga & Schooling, (2016) it is becoming more imperative to obtain information from embedded sensors within engineering infrastructure as well as earth structures to aid in the quantification of infrastructure performance.

Fibre optic sensors have various applications within the engineering industry and has successfully been used to monitor pipeline response due to tunnelling (Vorster, et al., 2006), monitoring seismic activity (Teisseyre, et al., 2006), monitoring a landslide location in Japan (Higuchi, et al., 2007), to estimate sinkhole-induced ground movements (Buchoud, et al., 2016), and to investigate slopes using fibre optic sensors (Arzu, et al., 2015; Kapogianni, et al., 2016a; Huang, et al., 2018).

Although the use of optic fibre sensors is not new technology, its use within the geotechnical community is a relatively new concept which competes well with current monitoring techniques since the optical fibre sensors are small, can survive chemically aggressive environments, is immune to electromagnet interference, and many different sensors can be multiplexed into one optical fibre (Chtcherbakov, 1997).

Optic fibre sensor monitoring systems can act as real-time early-warning systems as well as long-term monitoring systems and can accurately predict microstrain differences at various locations along an optic fibre cable (Picarelli, et al., 2015). Thus, the basic location of microstrain changes within geotechnical structures can be continuously monitored and the resultant microstrain measurements can be used to predict failure or identify localised failure zones.

The use of physical small-scale modelling to model geotechnical problems is seeing a growing trend within the geotechnical community whereby prototype structures are scaled down using similitude laws to simulate a real-life problem (Ozkahriman & Wartman, 2007). This has the benefits of studying complex, nonlinear geotechnical systems, boundary conditions and phenomena that are difficult to visualise (Wartman, 2006).

2 FIBRE OPTIC SENSING

Optic fibres are symmetrical cylindrical structures composed of a glass core, depicted in Figure 1, with a refractive index of 1 (n1). The glass core is enclosed by a material, termed "cladding", with a lower refractive index (n2), trapping all the light waves travelling through the medium in the glass core by reflection (Barrias, et al., 2016).

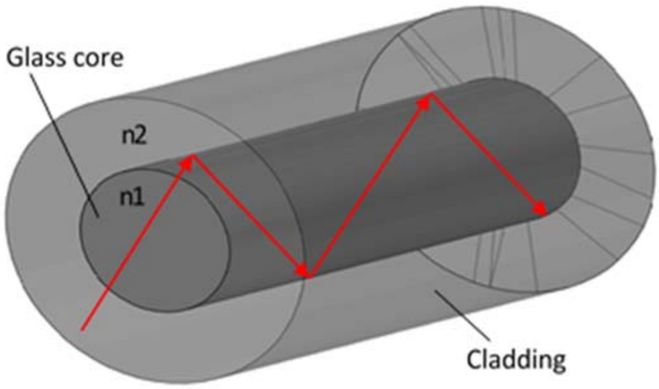

Figure 1. The working principles of optic fibre.

The light traveling within the fibre optic medium is emitted at a specific frequency by a laser and is contained within the glass core due to the cladding not absorbing any of the light. Thus, optic fibres operate on the principle of total internal reflection.

2.1 *Optical Time-Domain Reflectometry (OTDR)*

The main objective of an OTDR (Fig. 2a) is to measure the backscattering response of an optic fibre under test. The data obtained by the OTDR is subsequently displayed on the screen of the OTDR and the positional change within the optic fibre cable can be determined. It must be noted that an ideal optic fibre without breaks, splices or bends will be displayed as a straight line on the OTDR.

As strain is formed due to slope movement, the fibre optic medium will move and bend in the direction of the slope movement. This causes bends within the fibre optic medium which causes a phase shift of the light traveling through the medium where some of the light will undergo backscattering (Linker & Klar, 2017) in the direction of the light source. The reflection of the light allows for the detection of the location where movement took place.

2.2 *Fibre Bragg Grating (FBG) sensors*

An FBG sensing system uses periodically modulated sensors to detect changes along an optic fibre cable. The FBG reflects only a certain wavelength towards the source the light (Huang, et al., 2018). The wavelength of the light is either affected by strain or

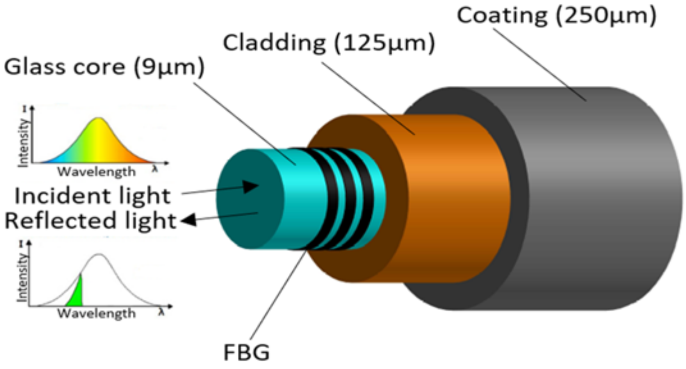

Figure 3. Depiction of the working principles of optic fibre with a fibre Bragg grating.

temperature. According to Udd & Spillman, (2011) the relationship between strain and temperature for a standard silica optical fibre is:

$$\frac{\Delta\lambda}{\lambda} = \beta\varepsilon + \xi\Delta T \qquad (1)$$

where λ is the original wavelength, Δλ is the change in wavelength, ε is the strain, ΔT is the change in temperature; β and ξ are the photo-elastic and thermo-optic coefficients for strain and temperature, respectively. (Udd & Spillman, 2011).

3 TESTING PROGRAM

The difference between OTDR sensing techniques and FBG sensing techniques is that FBGs are intrinsic optic fibre sensors created by irradiating the optical fibre core with UV light that periodically modulates the refractive index of the optical fibre at localised positions (Huang, et al., 2018).

These periodic modulations only reflect light with a wavelength matching the modulation period (Zheng, et al., 2018). FBGs can measure reliably as long as the optic fibre itself is coupled to the soil and has sufficient interface frictional contact (Schenato, et al., 2017).

For OTDR techniques, transmission loss is detected due to bending of the optical fibre (Higuchi, et al., 2007) whereas FBGs measure a wavelength change in the reflected light from the FBG due to temperature and strain changes (Huang, et al., 2018).

Figure 2. The system needed to create hetero-core sensors and monitor them. The system needed is: (a) Yokogawa AQ1000 OTDR (b) High precision cleaver (c) FSU 925 Fusion Splicer.

Figure 4. Model geometries for (a) Test 1 and test 3 (b) Test 2 and test 4. This picture also depicts the FBG sensor layout for (a) Test 3 (b) Test 4.

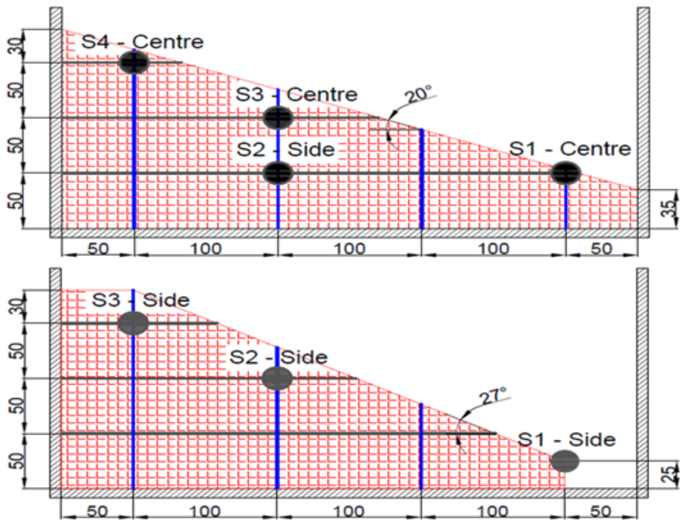

Figure 5. OTDR sensor layout for (a) Test 1 (b) Test 2.

3.1 *Small-scale physical model preparation*

The small-scale physical model, displayed in Figure 4, had a length of 400 mm, width of 300 m and a height of 180 mm. The simulation was lifted with a hydraulic jack at various angles to induce slope failure.

Two different geometries were used in order to simulate different boundary conditions and to avoid lateral constraints. For the tests done with the geometry depicted in Figure 4a, the toe of the slope did not have any free boundaries whereas tests done using the slope depicted in Figure 4b had a free boundary at the toe of the slope. The 50 mm × 25 mm high void (free boundary) was created by using a sponge until the entire slope was built. Thereafter, the sponge was taken out to create the free boundary at the toe of the slope. The soil would move slightly at the toe of the slope as the sponge was removed and the outcome, before testing commenced, is depicted in Figure 4b.

The soil used was sourced from Durban and was poorly-graded granular soil consisting of about 92% coarse sand and 5% medium gravel. The tests were carried out on dry cohesionless sand with a friction angle of 32º.

For testing purposes, the soil was placed in 50 mm thick layers and compacted while feeding the fibre optic cables through the soil. The optic fibre cable was pre-strained in order to measure the elongation as well as the contraction of the optic fibre cable. The dark layers of sand, depicted in Figure 4, show the layers where the sensors have been embedded for the various tests.

Once all the fibre optic cables were embedded and the soil was stacked to a height of about 180mm the simulation box was lifted to various angles to induce slope failure.

3.2 *Testing with an OTDR*

For test 1 and test 2 a Yokogawa AQ1000 OTDR (Fig. 2a) was used. To use the OTDR, sensors had to be manufactured by cleaving 150 mm single-mode optical fibre and 150 mm multi-mode optical fibre strands with a cleaver (Fig. 2b) after which the optic fibre strands were spliced together using an FSU 925 Fusion Splicer (Fig. 2c).

Single-mode and multi-mode optical fibres have different core sizes and by splicing these together a sensor with a bigger reflection is created. The setup in Figure 2 was used to create the hetero-core sensors. Since the splices were 150 mm apart, the sensors were 150 mm apart inside the simulation box. Thus, ideally the slope would be able to be monitored for every 150 mm of optic fibre length. The OTDR sensor layout is shown in Figure 5.

3.3 *Testing with FBGs*

For test 3 and test 4, FBGs were assembled using the setup depicted in Figure 6. Nine strain sensors were manufactured, and two temperature sensors were manufactured by removing a 20 mm piece of cladding from photosensitive optic fibre at the location where sensors were needed. The photosensitive optic fibre was then carefully placed and stretched across a phase mask. The optic fibre was thereafter connected to a circulator which was connected to a broadband source and an optical spectrum analyser. The optic fibre was then irradiated with UV light through the phase mask which printed a certain pattern onto the glass core. The said pattern acts as a sensor which is termed an FBG. The FBG was then coated with an epoxy and more FBGs were manufactured with the abovementioned process.

Nine strain sensors (S1-S9) and two temperature sensors (T1, T2) were manufactured. These sensors could be reused from test 3 to test 4. The sensors were placed in exactly the same locations for the different tests. The only exception was that the strain sensors 6 and 7 (S6 and S7), as depicted in Figure 4a, could not be used in Test 4 since the sensors would not have been embedded in any soil for the geometry in Figure 4b.

More sensors were embedded into the slope where more slope movement was expected. Since mostly shallow slides were induced, more strain sensors were embedded closer to the slope surface whereas deeper within the model less or no sensors were embedded at all. The temperature sensors were placed closer to the centroid of the slopes.

The FBGs had to be calibrated for strain as well as temperature. Therefore, strain calibrations were done by stretching an FBG 250 micron at a time and measuring the corresponding wavelength. Temperature calibrations were done by placing an FBG in boiling water and measuring the wavelength as the temperature went down. The sensitivity of the FBGs to strain and temperature was found to be1.2pm/$\mu\varepsilon$ and 8.52pm/ºC, respectively. Therefore, β was found to be 1.2 and ξ was found to be 8.52.

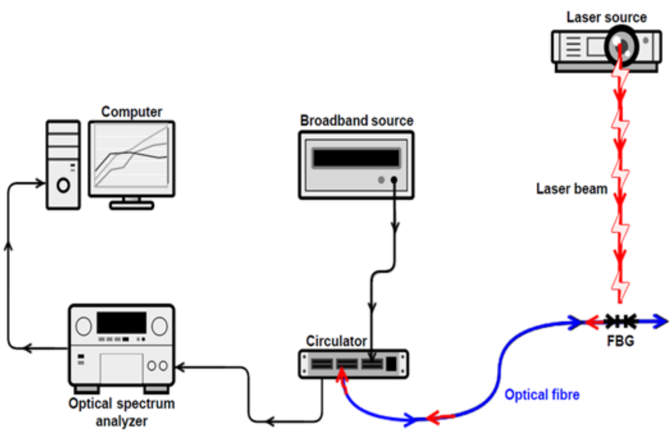

Figure 6. Setup showing how to assemble fibre Bragg gratings.

4 RESULTS

Before testing took place, for either of the tests, sensors had to be made and calibrated. For tests 1 and 2 a Yokogawa AQ1000 OTDR was used. For tests 3 and 4, a standard HBM FS22 Industrial Braggmeter was used with BraggMonitor SI software. For the OTDR system, Fiberizer software was used to manipulate the data.

For tests 1 and 2, OTDR testing was carried out by creating hetero-core optic fibre sensors by splicing 150 mm single-mode and multi-mode optic fibre pieces together until a 15 m long optic fibre cable was created. Hetero-core sensors were created in order to create greater reflections within the medium itself. Splices were further covered with an epoxy to protect the splices as well as to increase frictional contact between the optic fibre sensors and the soil.

Slope failure was induced by lifting the simulation box after the soil was placed. Control measurements were taken before testing commenced and the final measurements were taken after slope failure had been induced.

For test 1, failure took place at a simulation box inclination of 15º whereas for test 2, failure took place at a simulation box inclination of 7º.

Figure 7 showcases the results of the OTDR tests. The peaks on the data indicate splices. The first peak on the graph indicates the connector of the optic fibre cable to the OTDR. The last peak indicates the optic fibre cable end. Peaks between the start and end of the optic fibre should become smaller as the soil started failing. This is due to the optic fibre bending.

Therefore, more light is scattered within the bends of the optic fibre cable and less light is backscattered or reflected to the source. Movement was however, only recorded at splice number 4 for test 1. For test 2, movement was picked up at splice numbers 1 and 3.

Movement was detected where the peak of the test graph is lower than the peak of the control measurement. It must be noted that movement was not detected at all the sensor locations. This could be that the splices that were introduced into the optic fibre cable did not create a big enough response, or because of instrument resolution. It could also be due to many sharp bends being introduced into the optic fibre cable while embeddeding it into various soil layers.

For tests 3 and 4 FBGs were inscribed into the optic fibre core with UV laser light, using a phase mask technique. The sensors were placed at predetermined locations (see Figure 4 for the sensor layout).

For test 3, FBG sensors were manufactured on five different optic fibre cables. Nine strain sensors and two temperature sensors were manufactured. After the sensors were manufactured, they were coated with an epoxy to protect the sensors as well as to increase frictional contact between the optic fibre cable and the soil. The FBG sensors were then embedded into

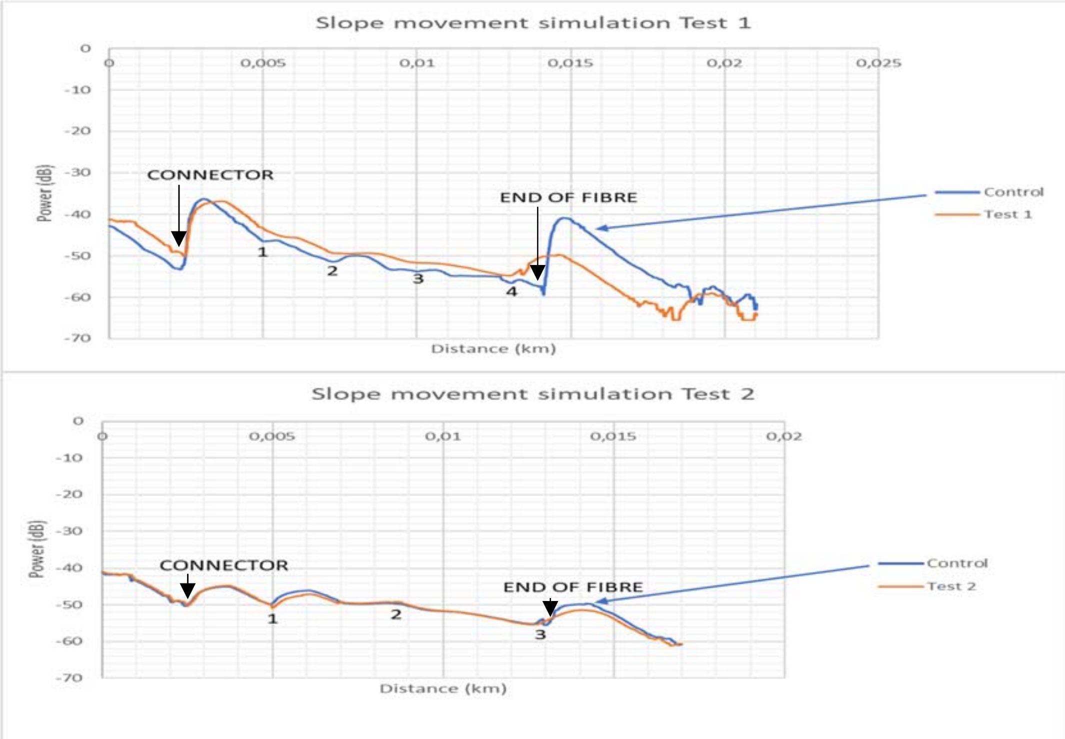

Figure 7. OTDR test results for test 1 and test 2.

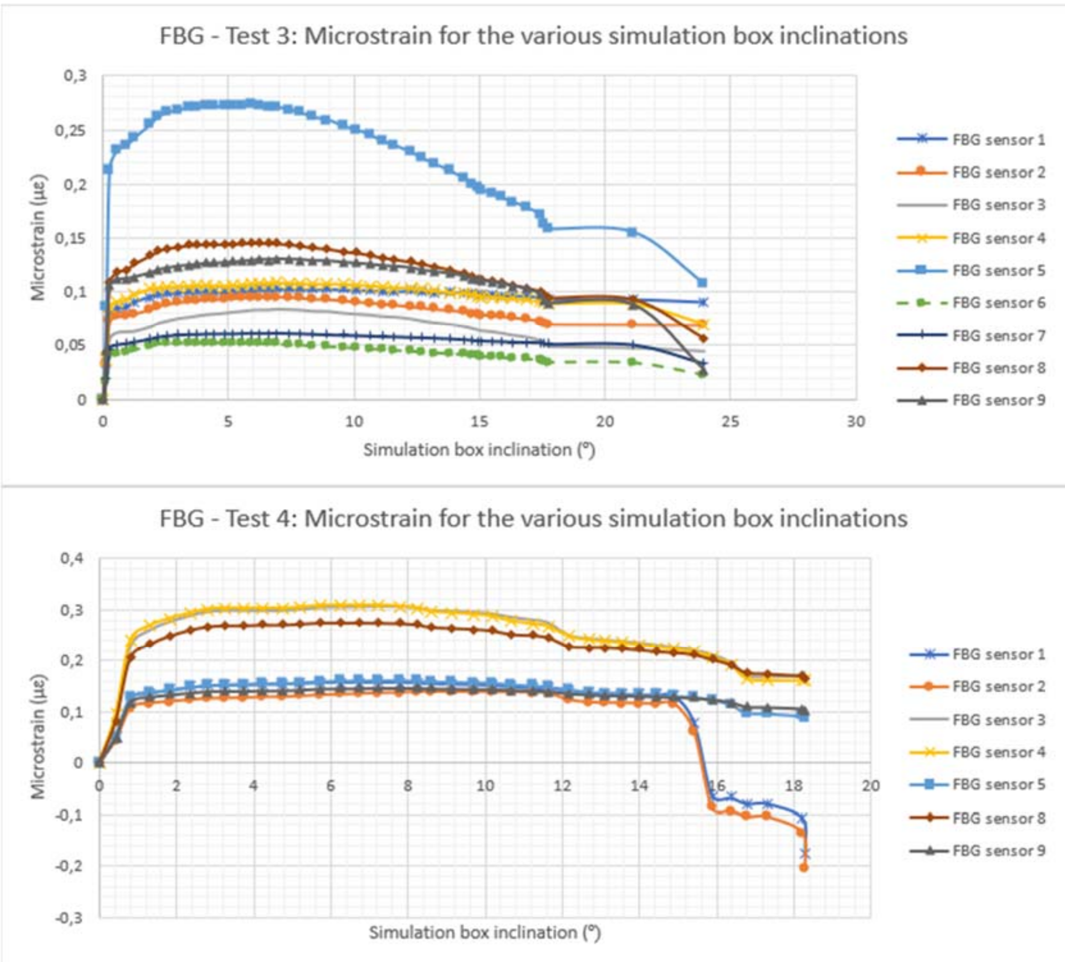

Figure 8. FBG strain test results for test 3 and test 4.

the various soil layers as shown in Figure 4. Thereafter, testing commenced by using a hydraulic jack to lift the simulation box to various inclinations while monitoring the FBGs.

Various slides were recorded for each test but for test 3, initial visual failure of the slope occurred at an angle of 15º and for test 4 initial visual failure of the slope occurred at 7º. As shown in Figure 8 the microstrain increased as the simulation box was lifted.

The microstrain would further remain roughly the same for all FBGs until visual failure occurred. Thereafter, the microstrain would reduce for the sensors with less soil on top of them due to slope movement. The results indicate that peak microstrain is reached before visual failure occurred.

The negative microstrain for sensor 1 and sensor 2 in test 4 was due to the sensors returning to their initial position as there was no more contact between sensors 1 and 2 and the soil.

Strain results for tests 3 and 4 compared well with strain trends displayed in Lienhart, (2015). It must be noted that Lienhart, (2015) monitored the construction of a reinforced earth structure during its construction phase as well as post-construction phase.

5 DISCUSSION & CONCLUSION

In the current study, OTDR techniques and calibrated FBG sensor technology was used to monitor slope movement in a small-scale physical model under normal gravitational conditions. These techniques offered a great advantage over traditional slope monitoring methods as the sensors could be embedded into the structure itself. This provided slope movement information at locations within the structure that would normally not be accessible if not for the sensitivity of the optic fibre sensing cables.

OTDR techniques proved to be able to monitor slope deformation but can only monitor movement through optical power loss. Furthermore, the FBG sensing technology proved to be very useful since microstrain could indirectly be measured in various layers of the geotechnical structure.

The FBG sensor technology indicated that deformation changes could be detected at early stages due to peak strain being reached before any visual failure occurred and leads to the possibility of being an early-warning system.

Future testing includes changing the weather conditions to which the geotechnical structure is subjected to and installing optic fibre cables in a project area.

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