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Measuring soil strain using fibre optic sensors

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Abstract. Monitoring subsurface soil movement is important in many geotechnical engineering applications such as stability of slopes, road embankments and settlement in foundations. Soil displacement measurement is also helpful in understanding the formation of shrinkage cracks. Clay soils undergo shrinkage during drying and experience substantial stresses and strains, which results in shrinkage cracks. This paper presents a novel approach to measure soil strain using Fibre Bragg grating (FBG) sensors. In the experiments described, FBG sensors have been used to investigate the strain development in clay during drying.

FBG sensors are fabricated in the core region of specially fabricated single mode low-loss germanium doped silicate optical fibres. The grating is the laser-inscribed region with a periodically varying refractive index, which reflects a specific light wavelength. Due to the applied strain, ϵ , there is a change in the wavelength which can be measured and directly proportional to strain.

Kaolin clay, mixed with water close to the liquid limit, was allowed to dry under room temperature. The specimens were prepared in thin, long linear shrinkage moulds. FBG sensors were placed inside soil at the centre of the specimen. The strain development during drying underwent four phases moving from compression to tension. An oscillating nature of strain was also observed throughout the drying process. Results obtained are useful to develop analytical solutions to describe stress-strain behavior of drying soil.

Keywords: clay, drying, fibre optic sensors, strain

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1. Introduction

Expansive soils undergo shrinking and swelling due to change in moisture content. The characteristics of shrink-swell behaviour is of great importance to serviceability of geotechnical structures. In Australia, about 20% of the total land area is covered by expansive soils [1]. Traditionally, shrink-swell potential is determined using shrinkage limit test and swelling test.

Determination of soil displacement and strain with conventional methods such as local displacement transducers (LDT) and strain gauges are challenging due to their limitations with electromagnetic interference and possibility of corrosion in the presence of water. Alternatively, researchers have used particle image velocimetry (PIV) technique [2-3], laser technology [4] and X-ray tomography [5] to measure soil movement. However, these methods too have limitations. PIV technique can only be used to measure surficial movements. Sub-surface movement can be observed with laser and X-ray technology, however, the measurement of local small strains is still challenging.

This paper investigates the possibility of using optical fibre sensors to measure soil strain during shrinkage. The type of sensors used is fibre Bragg grating (FBG) sensors. The application of FBG sensors to soil strain measurement is novel. Xu et al. [6] reported to have used FBG sensors in a modified triaxial apparatus. They attached the FBG sensors to a metal bender element which translated the soil strain to the optical cable. In the present study, FBG sensors were placed in direct contact with soil which was subjected to drying.

2. Fibre Bragg Grating (FBG) Sensors

Fibre Bragg Grating (FBG) sensors have been used for measuring strain of structures efficiently for more than two decades. The main application area of the sensors was limited to composite structures. Recent advances in FBG sensor technologies have provided great opportunities to develop more sophisticated strain monitoring systems for soil strain measurement and monitoring.

The diminutive FBG sensor, provides the ability to embed the sensors in soil samples without scarifying the material properties of the specimen. With the soil shrinkage, the embedded sensor compresses with soil and the respective strain in the soil is been measured by the sensor. This sensor is suitable for networking since it has a narrowband with wide wavelength operating range hence can be highly multiplexed, which is same fibre have multiple sensor locations along the length of the fibre. Multiplexed sensors can be used to measure strain along a soil sample at multiple locations using a single fibre. Since FBG sensors are nonconductive, they can be operated in electromagnetically noisy and/or wet environments without any effect. FBG sensor is made up of glass which is environmentally more stable and with a long life span. FBG sensor signal can be monitored from longer distances making it suitable for remote sensing due to its low transmission loss [7-9].

2.1 Principle of Bragg sensor

FBG sensors are fabricated in the core region of specially fabricated single mode low-loss germanium doped silicate optical fibres. The grating is the laser-inscribed region which has a periodically varying refractive index. This region reflects only a narrow band of light corresponding to the Bragg wavelength λ_B , which is related to the grating period Λ_0 [10].

$$\lambda_B = \frac{2n_o \Lambda_0}{k} \quad (1)$$

where k is the order of the grating and n_o is the initial refractive index of the core material prior to any applied strain.

Due to the applied strain, ϵ , there is a change in the wave length, $\Delta\lambda_B$, for the isothermal condition,

$$\frac{\Delta\lambda_B}{\lambda_B} = \epsilon P_e \quad (2)$$

where P_e is the strain optic coefficient and calculated as 0.793.

Fig. 1(a) shows reflected spectrums of an FBG sensor. Monitoring the peak wavelength allows the stain at that point to be calculated. Fig. 1(b) shows the change of the spectrum due to loading. Wave shift of the FBG sensors under loading is recorded and the readings are converted to strain using the equation 2.

Fig. 1 Reflected spectrum of an FBG sensor.

3. Materials and Shrinkage experiments

A series of drying shrinkage tests was conducted with kaoline clay. The consistency limits of kaoline are Liquid Limit (LL) 70% and Plastic Limit (PL) 42%. The specimen preparation was similar to linear shrinkage test. The moulds used in the current study were made of Perspex and rectangular in shape. The internal dimensions were $L = 250$ mm, $W = 25$ mm and $D = 18$ mm. A specimen prepared for testing is shown in Fig. 1(a).

Soil was prepared at a moisture content of 80%, slightly above the LL, in order to obtain a smooth and homogenous clay layer. A thin layer of petroleum gel was

applied to the base and the sides of the mould to allow free shrinkage. The specimens were kept on an electronic balance and were dried in the air under two flood-lights. Each test was carried out for about 36 hours.

It was decided to place the sensor at the centre of the specimen to minimise any boundary effects. The configuration is shown in Fig. 2(b). Approximately, 50 mm long segment of the optical fibre (including the 10 mm gauge length of the sensor) was buried inside clay. The sensor recorded 10 readings per second (10Hz).

Fig. 2 (a) Specimen prepared for testing (b) Location of the FBG sensor inside the soil layer (side view)

4. Results and Discussion

Strain measurements obtained during drying is shown in Fig. 3. The curve represents the average strains of all the tests conducted. For brevity, strains measured at 15 min intervals were used for plotting. The centre of the clay layer undergoes compressive strain for most part of the drying period. At the beginning of the tests, there is a short period, up to about 2 hrs, when the strain is tensile. This is due to the initial heating up of the clay layer. The specimens were prepared at room temperature which was in the range of 22° to 24° C. However, the temperature in the surrounding

of the experimental set up remained steady at 31.5°C due to the constant heat emitted by the lights. Therefore, the specimens experienced a warming up period resulting an expansion.

Fig. 3 Development of strain with drying time

The accuracy of measurements depends largely on how well the sensor is attached to clay. In the current study, visual observations indicated a fairly strong adherence between the sensor and soil. Additionally, the sensor recorded data from the very beginning of the test implying there was no slip. As the drying progressed, the adherence of sensor to soil strengthened further.

The curve in Fig. 3 suggests a smooth progression in strain development. However, a closer view will show that strains undergo fluctuations. Fig 4 and 5 show magnified sections of Fig. 3 at 300th and 1800th minute respectively. At the 300th minute, the specimen is subjected to increasing compressive strain. Fig. 4 shows the fluctuation during this minute with measurements taken at every 1 second.

Fig. 4 Strain oscillations observed within the 300th minute (5hrs)

Fig. 5 Strain oscillations observed within the 1800th minute (30 hrs)

By the 1800th minute, the strain at the middle of the specimen has started to undergo tensile strains. Fig. 5 shows the fluctuating behaviour within the selected minute. The fluctuations are more prominent at this stage. Similar observations were made by Costa and Kodikara [11] using PIV image analysis under restrained shrinkage conditions prior to desiccation crack initiation.

Fig. 6 Variation of strain with the moisture content change

Two observations can be made from the results shown in Fig. 4 and 5. First, strains of a drying soil element oscillates around a mean value. It is possible that these oscillations are inherent to drying shrinkage. Second, the mean value changes with the loss of water. This is initially compressive indicating a reduction in volume

due to removal of water (500th minute). Once the specimen has undergone substantial drying, the mean value takes a positive value (tensile) suggesting an increase in volume due to air entry (1800th minute). However, this volume increase occurs only locally as the overall result would be a reduction in volume for the whole specimen.

Fig. 6 shows the variation of strain as the moisture content reduced. It is possible to identify four phases of drying from this curve. Phase 1 refers to the initial period where the specimens undergo warming up as explained above. No significant development in strain can be seen at this phase. Strain is slightly tensile due to the expansion of pore water. The total moisture content reduces by about 10%.

As the specimen starts to lose water, the specimen undergo compression. This is evident in phase 2. The specimen loses nearly about 40% of its water during this phase. The shrinkage continues until the compressive strain reaches a maximum.

The third phase can be considered a relaxation phase. The middle of the specimen relieves compression. It is important to remember that this is apparent from a soil element at the centre of the specimen. The strain of the whole specimen is still compressive as the soil mass continues to shrink. A reduction of about 20% of moisture is evident during this phase.

Fig. 7 Variation of drying rate of the specimens with moisture content

The end of the relaxation phase marks the beginning of tensile strain development. By this time, the specimen has lost about 70% of its moisture and the drying process slows down as shown in Fig. 7.

In free shrinkage, tensile strain development (Phase 4) starts at a later stage. The specimen is close to its shrinkage limit by this time and cannot generate sufficient tensile stresses to cause a tensile failure. In other words, strain energy built up is not adequate to produce a fracture surface. Thus, the free shrinkage specimens rarely produce desiccation induced shrinkage cracks. When the shrinkage is restrained at the base (sometimes on sides as well), phase 4 is reached at an early stage while the specimens still have much moisture to lose. Consequently, the strain curve will continue to develop into a parabolic shape with a maximum tensile strain. This will

result in a similar stress profile as proposed by Kodikara and Choi [12]. If the specimen continue to dry having such a tensile stress profile, it will reach a state where tensile stress exceeds the tensile strength of the material causing a fracture.

5. Conclusions

Fibre optic sensors were successfully implemented to measure sub-surface strain in drying soil specimens. The development of strain at the centre of the specimens was determined. It is possible to identify four phases of strain development during drying: warming up, compression, relaxation and tension. Another interesting behaviour of strain was its oscillating nature. The strains oscillates around a mean value at any given instance.

While the FBG sensors produced reliable measurements, it is necessary to verify them using another method. The current study was limited to test the feasibility of FBG sensors to measure soil strain. Further investigations are needed to study the stress-strain behaviour of drying soil in detail.

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