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INTEGRATED PORE WATER PRESSURE AND GROUND SUBSIDENCE PROFILE MONITORING

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Over the past few decades, many optical fibre sensing techniques have been developed. Among these, optical fibre Bragg grating (FBG) is probably the most popular one. With its unique capabilities, FBG based geotechnical sensors can be used as an array for profile measurements, deployed under water (submersible), for localized high resolution and/or differential measurements. The authors have developed a series of FBG based transducers that include linear displacement and gauge/differential pore-pressure sensors. Techniques that involve the field deployment of FBG extension/contraction and pore-pressure sensor arrays for automated ground subsidence monitoring have been developed. The paper provides a background of FBG and the design concepts behind the FBG based field monitoring sensors. The case of field monitoring using the FBG sensor array in a single 100m deep borehole is presented, their practical implications are discussed.

INTRODUCTION

Most of the existing electrical sensor and cable systems are prone to adverse effects of electro-magnetic inference (EMI), short circuit, and lightning. Fibre optic sensors have features that are especially appealing for geotechnical field monitoring where the sensors are often subject to extreme or harsh conditions. Common drawbacks of the electrical sensors can be significantly and readily avoided when using the fibre optic sensors. Of the many available techniques, the authors have been concentrating on the use of Fibre Bragg Grating (FBG) as a core sensing element in their developments of a series of fibre optic sensored geotechnical field monitoring systems. Ground subsidence resulted from excessive groundwater pumping has been a serious problem in many parts of Southeast Asia and the rest of the world. Effective monitoring of ground subsidence for these cases often requires measurement of vertical ground displacement profile with great depth and preferably with concurrent pore water pressure measurements. Available techniques hitherto before have not been able to fulfil these requirements. This paper provides a brief background of FBG and presents the experiences in the application of FBG ground subsidence monitoring system developed by the authors.

FBG AS A PARTIALLY DISTRIBUTIVE STRAIN SENSOR

Optical fibres are made of silica, with a diameter about the same of a human hair, and can transmit light over long distances with very little loss of fidelity. Optical fibres comprise two essential components: a core surrounded by an annular cladding. The core of the optical fibre serves to guide light along the length of the optical fibre. The cladding has a slightly lower index of refraction than the core. Its primary function is to ensure total internal reflection within the core and that very little light is lost as it propagates along the core of the optical fibre. The typical combined diameter of core and cladding is 125 μm. The silica core/cladding is protected by an acrylic coating. The total outside diameter of an optical fibre with the acrylic coating is 250 μm. By adopting technologies from telecommunication, many fibre optic based sensing techniques have been developed. The fibre optic Bragg grating (FBG) is one of the many available forms of optical fibre sensors. An FBG is made by a periodic variation of fibre core refractive index. The typical length of an FBG is 1 to 20 mm long. When the FBG is illuminated by a wideband light source, a fraction of the light is reflected back upon interference by the FBG. The wavelength of the reflected light, is linearly related to the longitudinal strains of the FBG, thus making FBG an ideal strain gage. The returned signal from every FBG carries a unique domain of wavelength, making it possible to have multiple FBG elements on the same fibre. The multiplexing among various sensors on a single fibre can be accomplished by wavelength division addressing as conceptually described in Figure 1. The FBG is partially distributive because only those parts of the optical fibre with FBG are used as strain sensors and these sensors can share the same optical fibre transmission line.

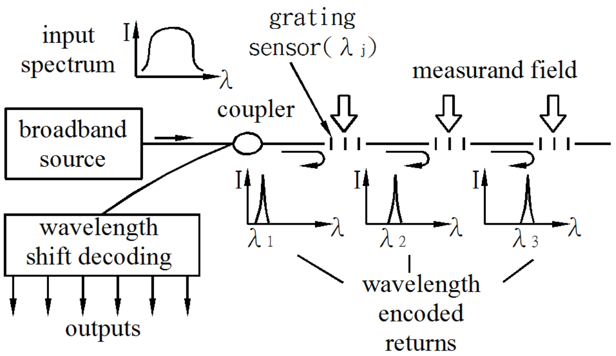

Figure 1. Schematic diagram of Fibre Bragg Grating (after Kersey [1]),
I = light intensity λ = wavelength.

FBG SENSORED FIELD MONITORING DEVICES

The FBG can be used directly as a strain gage, or, with the help of mechanical components, FBG can be configured as displacement, pressure or inclination transducers (Ho et al. [2]&[3]). All advantages of the FBG can be inherited in FBG-based transducers for geotechnical engineering monitoring purposes. These advantages can include: partially distributive, high resolution, good signal stability and immunity to EMI. The FBG based sensors can be used as an individual sensor to reflect the physical quantity at a given location or connected into an array so that the profile of a given or multiple types of physical quantities can be monitored. The following section describes two FBG the based transducers developed by the authors that relate to ground subsidence monitoring.

The FBG Pressure Transducer

Figure 2 shows a schematic view and photograph of an FBG pressure transducer. The FBG was used to sense the deflection of a metallic diaphragm inside of the transducer due to changes in pressure against the atmosphere. A separate FBG was placed inside the transducer to monitor temperature fluctuations. The measuring range of the pressure transducer was controlled by the stiffness of the diaphragm. The FBG pressure transducers were used in the integrated ground subsidence monitoring system as piezometers.

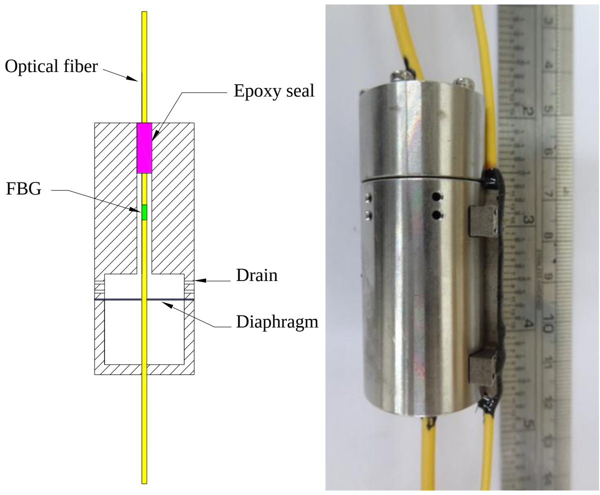

Figure 2. The FBG pressure transducer.

The FBG Extensometer

The FBG extensometer as shown in Figure 3 was developed to measure linear extension or compression. The linear movement induces relative motion between a roller and a wedge that in turn creates bending to a spring leaf. A pair of FBG attached to the spring leaf was used to measure bending of the spring leaf, where the amount of linear displacement was deduced from. Two pairs of spring leafs, separated by 180 degree were used for extension and compression measurement. The device was built to have a linear resolution of 15 μm, and a full range of 40mm in compression and 20mm in extension.

GROUND SUBSIDENCE MONITORING AT GUAN-FU ELEMENTARY SCHOOL

Guan-Fu elementary school is located at the heart of an area in Central Western Taiwan, where the ground subsidence was the most significant in the island. From 1999 to 2011, the accumulated subsidence was approximately 900mm. The alluvial soil deposit in this region is expected to be more than 1000m thick. Although, excessive ground water pumping is believed to the main reason for ground subsidence. The soil deposit was mostly granular with various amounts of fines (particles passing #200 sieve). It is thus difficult to attribute the settlement to soil consolidation typically occurs in cohesive soils. In order to ascertain the mechanisms of ground subsidence, the magnetic rings and SONDEX sensor probe have been used to measure the ground settlement profile manually. Boreholes extending to a maximum depth of 300 m have been used for the purpose. The metal tape and SONDEX measurement system had a resolution of 1 mm and repeatability of ±4 mm. Groundwater levels were observed in a nearby, but separate borehole. Open-end piezometers, with a maximum number of 3, have been installed at selected depths to provide corresponding groundwater levels. Because of the deficiency in measurement resolution and miss-match between settlement and pore water pressure measurement depth frequencies, rigorous interpretation of the observed data has been difficult.

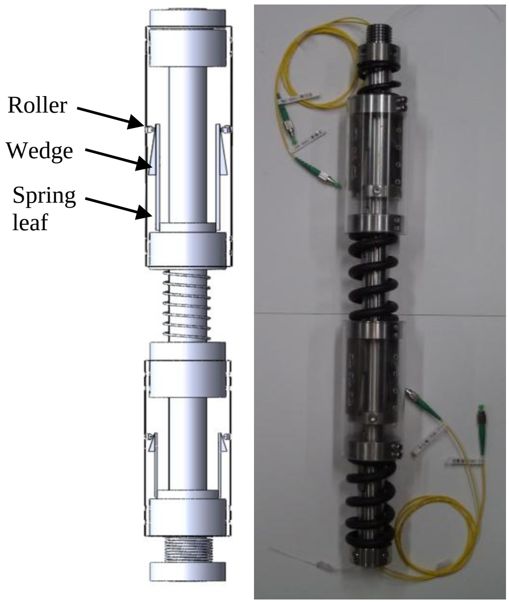

Figure 3. The FBG extensometer.

As a trial project, the authors developed and installed a 100 m deep FBG ground subsidence monitoring array (schemetically shown in Figure 4) at the Guan-Fu elementary school test site. This sensor array consists of ten repeating segments of FBG extensometers and FBG piezometers. Each segment contains a 10m long, 100 mm OD and 80 mm ID plastic pipe. The FBG extensometer is attached to the bottom of the 10m long plastic pipe. The pipe was equipped with friction rings, spaced at 2 m to increase grip between the plastic pipe and the surrounding soil. An FBG pressure transducer was installed at the middle of each 10m plastic pipe to serve as the piezometer. Holes were drilled in the pipe surrounding the piezometer and wrapped by non-woven geotextile that serves as a filter. The space between the borehole and plastic pipe was filled with sand to facilitate pore water pressure measurement for the piezometers. Bentonite was used as sealing at depths just below and above the piezometers. Field installation of the FBG ground subsidence monitoring array (see Figure 4) was completely on April 26, 2012. The installation enables pore water pressure and ground subsidence readings be taken simultaneously and within the same borehole.

By connecting the sensors to an FBG data logger (i.e., FBG interrogator), readings can be taken automatically on a real-time basis and transmitted via internet. The sensor readings reached stable values towards the middle of July. In analyzing of the data, ground subsidence at the bottom of the 100m borehole was assumed to be zero. The amount of subsidence accumulated according to the readings taken at every extensometers. Figure 5 depicts the pore water pressure and ground settlement profile radings on a monthly basis using the July 23 readings as a reference. The groundwater table was located at approximately 9m below ground surface. Figure 5 shows a clear deficiency in pore water pressure, in comparison with the hydrostatic pressure distribution. This defficiency explains the pre-existing and severe ground subsidence. From July 23 till the end of Octoder, however, the pore water pressure was increasing. The most significant increase occurred in August when a typhoon passed this area and brought approximately 900mm of rainfall. Corresponding to the increase of pore water pressure, the ground actually heaved (negative subsidence) by as much as 18mm near the ground surface. Manual SONDEX readings taken at a nearby borehole also showed heaving of 6.5mm at 30m below ground surface, from the middle of July to end of September.

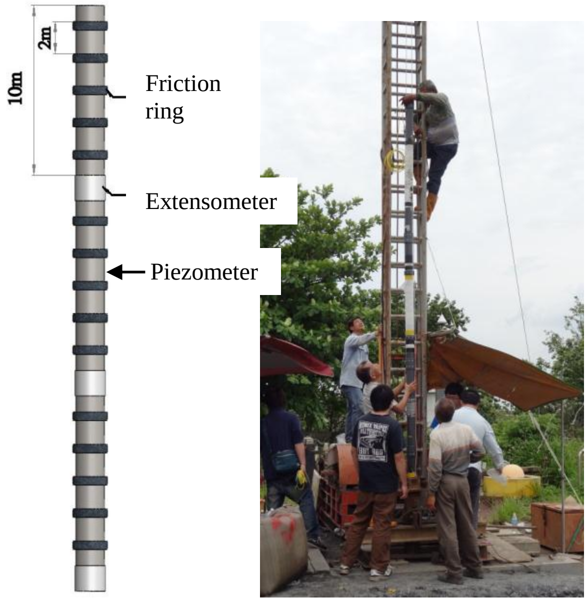

Figure 4 Field installation of the integrated FBG ground subsidence monitoring array.

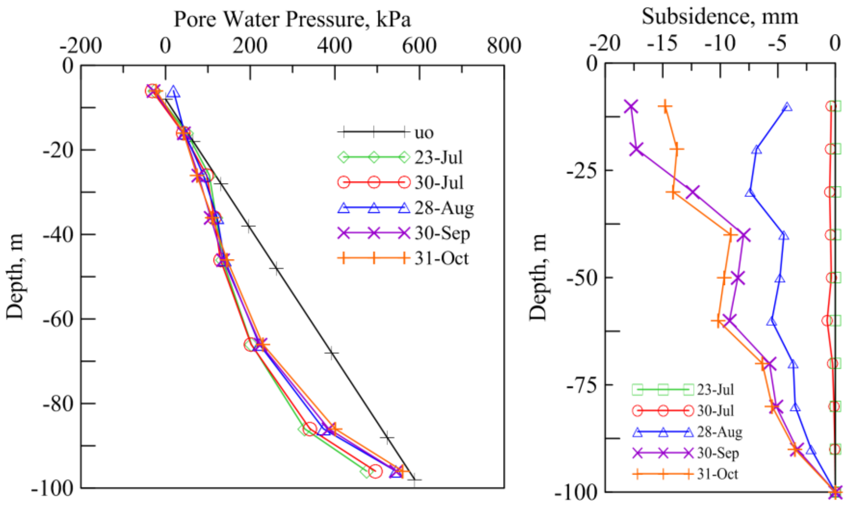

Figure 5. Pore water pressure and ground subsidence profiles.

Figure 6 demonstrates a history of 24 hour readings taken between 00:00 and 24:00 on August 28, 2012. The data show fluctuations by as much as 3.5 kPa in the change of pore water pressure (Δu) at depths from -26 to -36m, from 7 to 9 am and from 3 to 8 pm. This is believed to be a result of groundwater pumping by nearby farmers at their residences before and after field work. There is no other fresh water supply system in the area. There appears to be sub-mm (less than 0.15mm) ground subsidence/heaving following the fluctuation of pore water pressure.

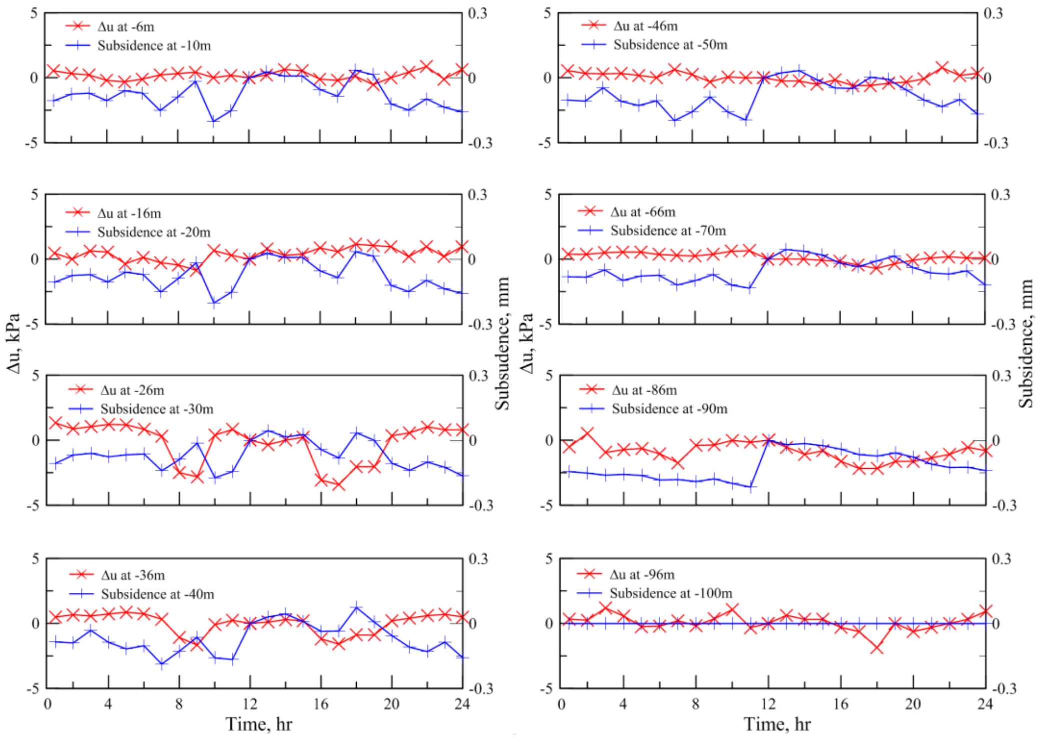

Figure 6. Time history of pore water pressure and ground subsidence within 24 hours.

CONCLUDING REMARKS

The experience shows that with the help of partially distributive sensors, field pore-water pressure and subsidence profile monitoring can be practically implemented. The integrated, simultaneous profile measurements provide real-time data that can readily be used to analyze the potential mechanisms or causes for ground subsidence.

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