Fibre Optic Technology in Geosynthetic Instrumentation for Monitoring of Soil Structures

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Abstract: It has always been envisaged if technology can provide impregnation of sensors into engineering materials, so as to become an intrinsic part of the parent material itself, for measurements of stresses or strains in the material. With the advent of fibre optic technology, this conceived idea has become a reality in a composite reinforcement geosynthetic. This paper looks at fibre optic technology and how a once single functioned geosynthetic for soil reinforcement, can now provide both reinforcement and measurement functions simultaneously, without the need for complicated placement of measurement sensors and cumbersome calibration. This technology offers huge advantages to engineers and makes instrumentation of geosynthetic reinforced soil structures and soil structures effortless to help mitigate disaster in the event of potential landslide or failure problems.

1 INTRODUCTION

With the increasing use of geosynthetics for reinforcement of soil structures, instrumentation on geosynthetics to monitor their behavior and their interaction with the soil, have been a challenging task for engineers. Unlike steel or concrete, the polymeric and non-homogeneous disposition of some geosynthetics, make reliable and robust instrumentation on geosynthetics difficult. The combined technology of using optical fibre and geosynthetics has made the reinforcement and monitoring of soil structures simultaneously, possible. Using special manufacturing technique, the incorporation of optical fibre; complete with strain sensors, into the reinforcement geosynthetic enables the measurement of strains in the geosynthetic, without the need of complicated placement of measurement sensors and cumbersome calibration.

This technology offers huge advantages to engineers and makes instrumentation of geosynthetic reinforced soil structures and soil structures effortless. It also provides opportunity for remote data acquisition and the implementation of early warning system to help mitigate disaster in the event of potential failure problems. This paper provides information on the technology and shows the simplicity of the technology in providing accurate and reliable measurements. The durability of the optical fibre under normal construction conditions is also assessed. Several application examples are given to demonstrate the versatility of the geosynthetic in reinforcing and monitoring soil structures.

2 OPTICAL TECHNOLOGY

The use of optical fibres for monitoring engineering structures expanded in the 1980s. Various monitoring devices were developed. The sensors in the optical fibre used for the strain measurements of geosynthetics employs the technique of Fibre Bragg Gratings (FBG).

FBG is diffracting element printed in the photosensitive core of a single mode optical fibre. If light of a broadband source (large spectral width) is transmitted into an optical fibre with a FBG, only the spectral component satisfying the Bragg relation will be reflected by the grating. The grating reflects a spectral peak based on the grating spacing; therefore, changes in the length of the fibre due to tension or compression will change the grating spacing and the wavelength (λ) of light that is reflected back (Briançon *et al.*, 2004). As a result, quantitative strain measurements can be made by measuring the centre wavelength of the reflected spectral peak (Fig. 1).

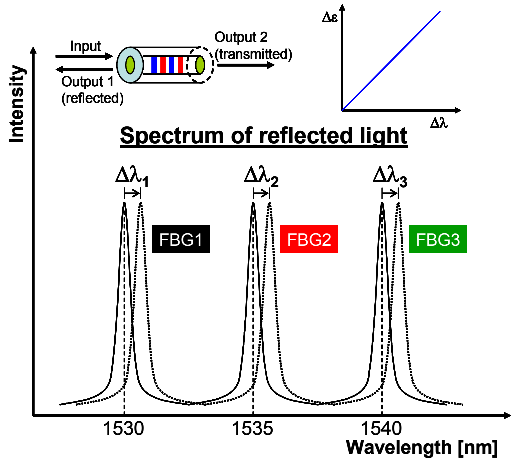

Fig. 1 Principle of Fibre Bragg Grating (FBG) sensors

An interesting feature is that by using different wavelengths (λ_1, λ_2, λ_3 etc.), signals of various FBG sensors can be identified and distinguished. Because each sensor has its own characteristic wavelength, the sensors can be integrated in series along one optical fibre line. The wavelength or wavelength-shift in each individual sensor can be measured using an interrogation unit within a specific wavelength domain. In this way, several sensors can be measured simultaneously and the location of the strains identified.

3 ‘INTELLIGENT’ GEOSYNTHETIC

To integrate strain sensors so as to become an intrinsic part of the geosynthetic, and thus, an ‘intelligent’ geosynthetic, continuous length optical fibre impregnated with FBG sensors, is inserted into a reinforcement geosynthetic using special manufacturing process (Fig. 2). As the FBGs are laser impregnated, the characteristic of every FBG is consistent to one another and calibration of wavelength versus strain need only be conducted on one FBG. In this way inconsistent placement of sensors on the geosynthetic and complicated calibration required for every sensor, such as that encountered using conventional method of instrumentation is avoided. The accuracy of measurements is therefore not compromised.

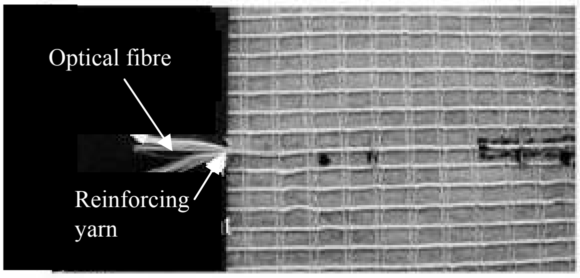

Fig. 2 Optical fibre inserted in a reinforcement geosynthetic through a special manufacturing process to form ‘intelligent’ geosynthetic

3.1 *Accuracy and reliability of measurements*

In a series of plane strain compression (PSC) tests on polymer geosynthetic-reinforced sand conducted at the Tokyo University of Science, FBG sensors were used to measure the mobilised tensile strain in the geosynthetic layer, Kongkitkul *et al*. (2006). The main objective of the investigation is to study the interaction between the soil and polymer geosynthetic reinforcement, as both soil (Tatsuoka *et al*., 2002) and polymer geosynthetic (Hirakawa *et al*., 2003; Kongkitkul *et al*., 2004, Shinoda & Bathurst, 2004) have significantly viscous behaviour (e.g., creep deformation and stress relaxation), not only during monotonic loading at a strain rate but also during sustained loading of the reinforced sand.

Advantages of using FBG sensors in the PSC test are that they can be connected in series by a single cable while still be able to identify the different mobilised tensile strain from the different designated locations (Fig. 3) and therefore they provided a better workability than when using strain gauges with electrical wires. The latter becomes outstanding when using in laboratory as the working space is usually limited.

The test results showed a good response of the FGB sensors corresponding to various stages of loading: a) primary monotonic loading; b) intermission by sustained loading; and c) monotonic loading that resumed after sustained loading (Figs. 4(a) and (b)). More importantly, FBG measurements showed that, during sustained loading of reinforced PSC specimen, the mobilised tensile strain of polymer geosynthetic significantly decreased with time. Similar trend of behaviour was also observed by using strain gauges attached with geogrid reinforcement (Kanemaru *et al*., 2006). Therefore, the effects of tensile load relaxation when arranged in sand subjected to sustained loading are significant and the FBG sensors provided easy and reliable measurements compared to using conventional instrumentation techniques such as strain gauges.

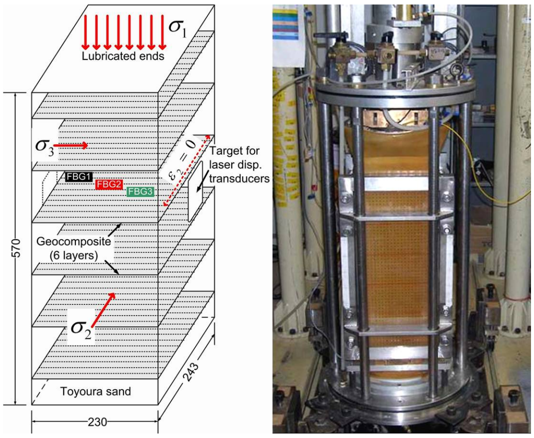

Fig. 3 Geosynthetic reinforced PSC specimen and locations of FBG sensors (Kongkitkul *et al*, 2006)

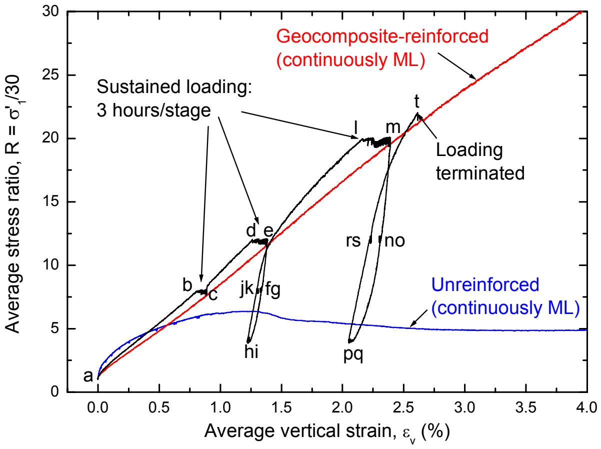

Fig. 4(a) Average stress ratio – average vertical strain relation of geosynthetic reinforced sand in PSC (Kongkitkul *et al*, 2006)

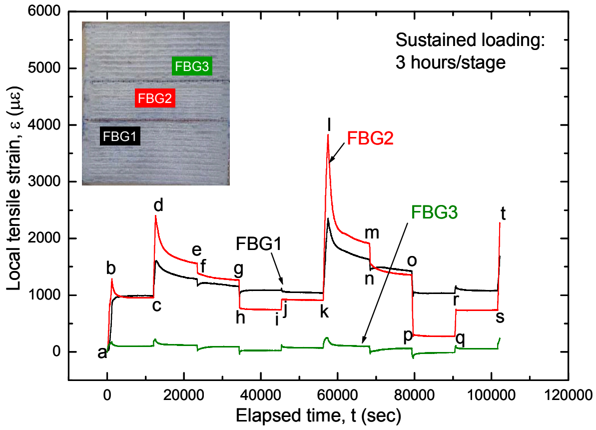

Fig. 4(b) Time histories of local tensile strains in three yarns measured by using FBG sensors (Kongkitkul *et al*, 2006)

The investigation by Kongkitkul *et al* 2006 showed the accuracy and reliability of measurements using ‘intelligent’ geosynthetic. A big advantage derived from this investigation was the ease of implementation of built-in sensor geosynthetic that provides reinforcement and monitoring simultaneously, in space constrained laboratory testing with minimum compromise on the accuracy of the results.

3.2 *Durability Assessment*

Comprehensive on-site damage and durability assessment on the 'intelligent' geosynthetic was conducted at Nancy, France and were reported by Briançon *et al.*, 2004. In this full-scale experiment, soil cover of gravel (20/40mm) was set up in two 0.25m thick layers over the geosynthetic and compaction was carried out in several phases (passes without vibration, with small vibration and intense vibration). Measurements of strain were recorded throughout the various phases of the installation. A maximum strain of 0.15% was measured. Under normal compaction conditions, no rupture of the fibre optic was observed. However, during the phase of intense compaction (above the normal required), rupture of an optical fibre was observed. The rupture was located under the area where the compactor stopped and turned round between two compaction phases. The full-scale experiment highlighted that where heavy compaction is anticipated, a protective sand layer over the geosynthetic is required.

4 ENSURING SAFETY IN SOIL STRUCTURES

The potential of 'intelligent geosynthetic' has been realized in several civil engineering projects such as monitoring of reinforced base embankment, and strain measurements in reinforced soil walls and slopes.

4.1 *Monitoring of Cavities Under Railway Embankment.*

The 'intelligent' geosynthetic was placed at the base of the railway embankment for high-speed trains. The embankment was constructed over cavity prone areas. Collapsed soil at the base of the embankment due to formation of cavities was supported by the geosynthetic. The monitoring sensors in the geosynthetic were used to detect the presence and development of cavities. The strains measured by the sensors were related mathematically to the size of the cavity that develops with time. Depending on the size of the cavity, an early warning system was implemented by setting a strain limit exerted in the geosynthetic. Once the strain threshold is reached, a warning will be triggered and the train operation will be stopped before significant settlement at the top of the embankment occurs (Fig. 5).

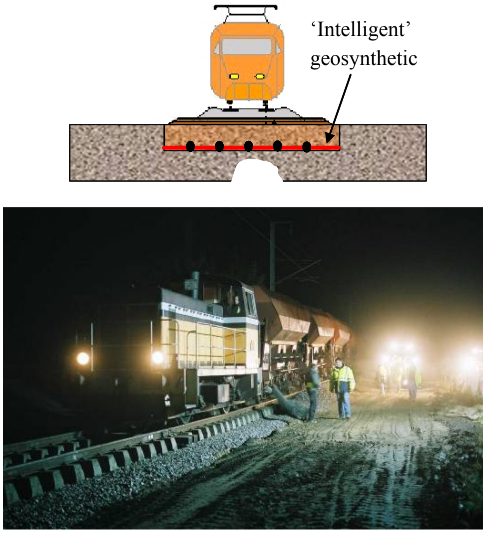

Fig. 5 Reinforcing base embankment against cavities and monitoring formation of cavities

4.2 *Monitoring the behavior of engineered reinforced soil structures*

The problems confronting engineers on the post construction strains of engineered reinforced soil structures are now over with the use of 'intelligent' geosynthetic. Geosynthetic panels with fibre optic strain sensors are placed at pre-designed locations in the soil as part of the geosynthetic reinforcement system to determine the development of strains in the structure (Fig. 6(a)). Where other geosynthetics are used as the soil reinforcement system, a strip of 'intelligent' geosynthetic of compatible tensile strength can be placed adjacent to the reinforcement system as shown in Fig. 6(b). A minimum of three layers of 'intelligent' geosynthetic are recommended in a vertical section of the structure, in order to determine the plane of maximum strain in the structure. The vertical spacing of the geosynthetic depends on the height of the structure.

Fig. 6(a) 'Intelligent' geosynthetic placed in the structure as part of the soil reinforcement system

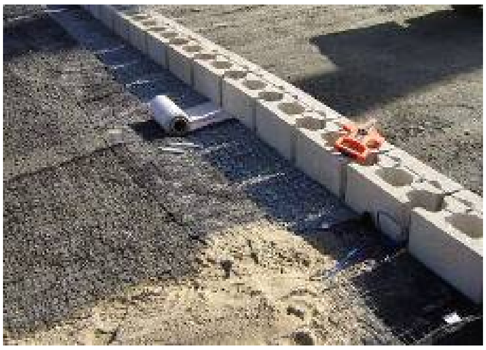

Fig 6(b) 'Intelligent' geosynthetic compliments other soil reinforcement system and providing strain measurements

4.3 *Monitoring of existing slopes*

Monitoring of existing or cut slopes of potentially high risk to landslide can be facilitated using 'intelligent' geosynthetic. In such applications, trench is excavated to the face of the slope at the top of the slope for placement of the geosynthetic strip. Several trenches spaced horizontally can be excavated along the top of the slope for geosynthetic instrumentation to map the horizontal profile of the slope movement as shown Fig. 7.

Fig.7 Trench excavated at the top of slope for placement of the geosynthetic to monitor movements of existing slope

4.4 *Remote Data Acquisition and Early Warning System*

Constant monitoring and post construction management of civil engineering earth structures can be implemented using 'intelligent' geosynthetic.

With the integration of telemetry, any strains developed in the 'intelligent' geosynthetic embedded in the structure can be transmitted to a remote computer terminal for remote data acquisition. The telemetry system consist a remote terminal unit (RTU) that decodes the signal recorded in the spectrum analyzer (measuring device). The decoded signals are transmitted to a remote computer unit via radio, GPRS or satellite; the mode of transmission is dependent on availability of servicing networks or cables at the project site. The system allows strain threshold limits to be set and thus an early warning system can be activated when the threshold is reached prior to failure of the earth structure (Fig. 8). The inclusion of telemetry, for remote data acquisition and early warnings, completes all the components of a monitoring system, and further enhance the application of 'intelligent' geosynthetic on the critical state of the structure for preventive maintenance and to avoid potential failures. This is of paramount importance to reduce economical lost and possibly save lives.

5 CONCLUSIONS

The simplicity and versatility of 'intelligent' geosynthetic as a reinforcement with build-in strain sensors provides safer construction of civil engineering structures. It offers wide applications such as road and railway embankments constructed on foundation prone to excessive settlements, piled embankments reinforced with geosynthetics, monitoring of soil subsidence, ground sinkholes and cavities, engineered walls and slopes and existing cut slopes and other structures such as underground pipelines and bridges. It makes instrumentation of geosynthetic reinforced soil structures and soil structures effortless, economical and avoids the complication of conventional instrumentation problems that confront engineers (Fig. 9). It delivers accurate and reliable measurements long term, and provides opportunity for remote data acquisition and the implementation of early warning system to help mitigate disaster in the event of potential failure problems.

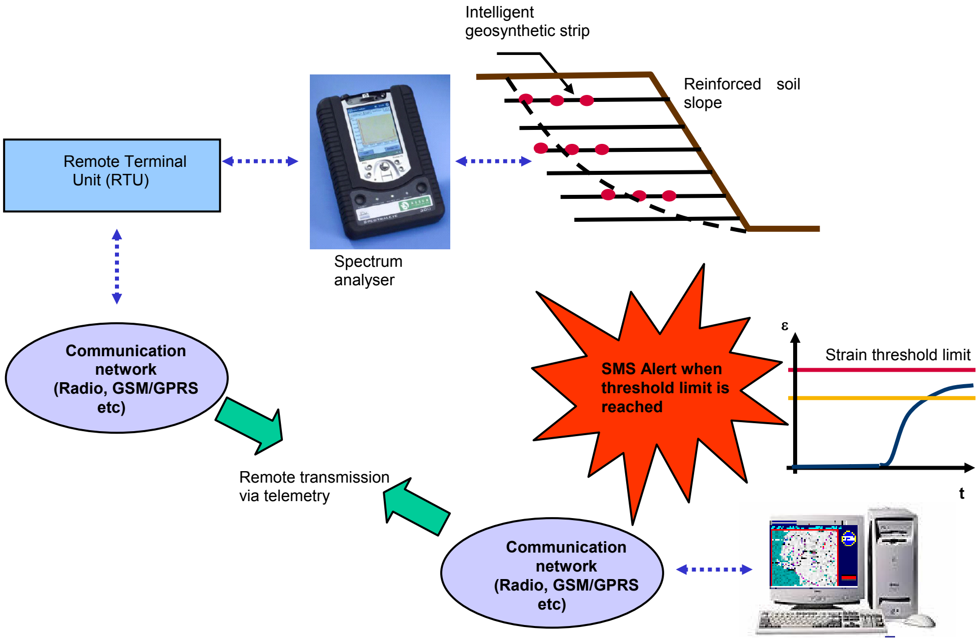

Fig.8 Monitoring of reinforced soil structures via telemetry for remote data acquisition and early warning system

Fig. 9 Complication of conventional instrumentation in monitoring of soil structures

ACKNOWLEDGMENTS

The ‘intelligent’ geosynthetic was honored with the Joint Research Innovation Award 2006 by the Prime Minister’s Department, Malaysian Administrative Modernisation and Management Planning Unit (MAMPU), Malaysia. Acknowledgement and appreciation is given to the Government of Malaysia for the award.

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