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PROCEEDINGS

GEOTEXTILE AND OPTIC FIBERS: FEEDBACK AFTER FOUR YEARS OF USE IN SOIL

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ABSTRACT

« Geodetect » is an innovative system for strain measurement of geosynthetics in soil. It is based on optic technology with optic fibers embedded in reinforcement geosynthetic. During its development, numerous tests and experiments have been carried out, particularly at the Laboratoire Régional des Ponts et Chaussées de Nancy (LRPC Nancy) and at the University of Grenoble. Following the system description and discussion of the strain measurement principles using fiber Bragg gratings, validating test results and project observations are shown for projects in service since 2003. Potential homeland defense applications are proposed following the project observations.
Keywords: strain, measure, reinforcement, monitoring, durability

INTRODUCTION

The understanding of the geosynthetic behavior in soil, especially when placed in civil engineering works, has always been a critical request and of great interest for owners and users. Monitoring is necessary to have a better knowledge of the processes involved. An accurate monitoring of civil engineering works allows one either to evaluate their actual safety level and optimize the design, or to survey the behavior of a structure which may be susceptible to change during time. The instrumentation of geosynthetic reinforced soil structures (reinforced slopes and walls, embankments on soft ground) has been done for many years through traditional systems such as strain gauges or displacement sensors. These systems are generally only used for experimentation or during the construction stage for a short period of time. Limitations to these traditional instruments are both the time-consuming installation and a short service life of only a few months. They are also only discrete monitoring points, making the survey of large areas difficult due mainly to the installation itself. Furthermore, the installation and adhering of the sensors on the geosynthetics may have a negative influence on the measurement accuracy due to their size. Additionally, the durability of these traditional devices is generally very limited if sophisticated protection is not used. Today, the need of survey and instrumentation justify the research and development of more accurate tools, easy to install and allowing long term performance. In this context, a new type of geosynthetic was developed for civil engineering applications, combining the performance of the technical geosynthetic and optical technology for measurement of strain in soil and for the survey of reinforced earth construction. This project was named “Geodetect” and was given the label Eureka (Σ! 2579/F958) in 2001. It was sponsored by the Ministry of Industries (ANVAR) and the Ministry of Road Equipment (DRAST) in France, as well as the Belgian Ministry of Industry, IWT. The result of two years of development, presented herein, consist of a reinforcing geosynthetic manufactured with optical fibers included in its production. The fiber optic lines are attached in a mechanical process which creates a very strong bond with the geosynthetic and therefore an accurate measure of the elongation. Thus, Geodetect offers an accurate measurement system that can be easily adapted to monitoring very large areas or areas of reduced size based on project specific requirements. Geodetect also offers the possibility of inserting a number of fiber optic lines at different reinforcement elevations. The validation of the system started in 2002 with experiments performed at the LRPC Nancy (France) and was followed in 2003 by varying loading applications in the experiment. During a site visit in 2005, no change in the behavior and the performance of the Geodetect system was observed. After the development phase, this new concept of measurement was installed at 15 other sites, approximately half which were actual projects and half which were further experiments. This paper will discuss some of the system validation steps and the understanding gained from actual civil engineering applications.

DESCRIPTION OF THE SYSTEM

Measurement principles

The design philosophy was to monitor the deformation of the geosynthetics through the strain measured directly in an attached optic fiber. This is possible using Fiber Bragg Gratings (FBGs) technology. Fiber Bragg Gratings are diffracting elements located in the photosensitive core of a single mode optical fiber. The FBG reflects a spectral peak based on the grating spacing. Thus, changes in the length of the fiber due to tension or compression will change the grating spacing and the wavelength of the reflected light (Fig. 1). Measuring the center wavelength of the reflected spectral peak allows quantitative strain measurements.

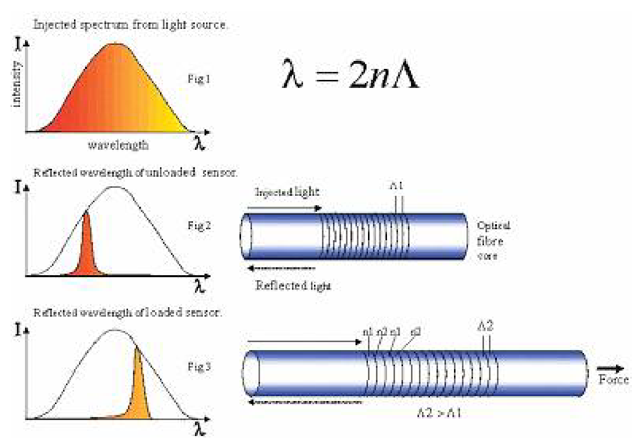


Figure 1. FBG response as function of strain.

Thus, a Fiber Bragg Grating can also constitute a sensor. The calibration curve of a sensor (Figure 2) shows that the displacement wavelength is proportional to the deformation of the fiber.

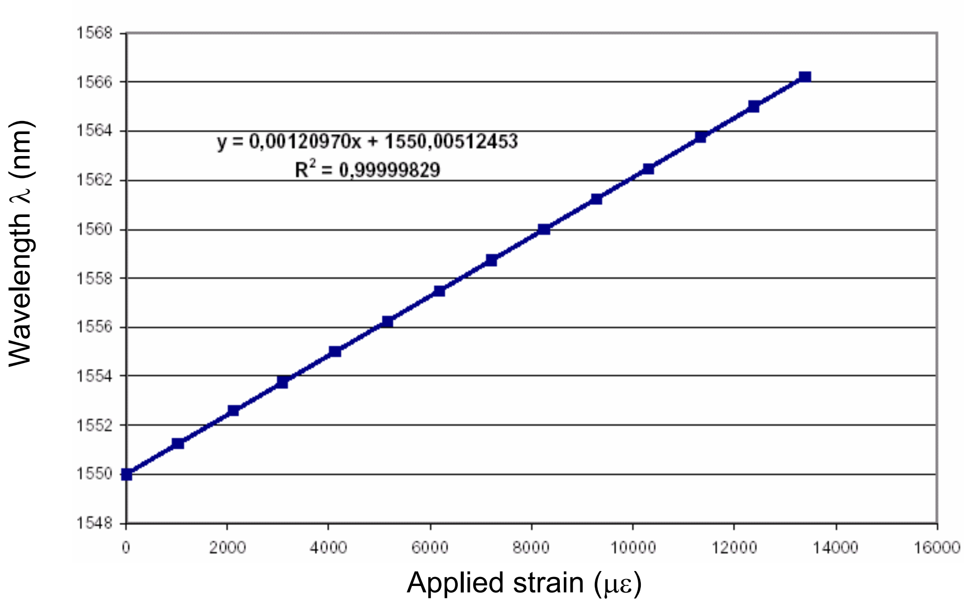


Figure 2. Correlation deformation - displacement wavelength of a Fiber Bragg Grating network.

The relation between the deformation ε (in ~~nm~~λ) and the wavelength λ (in nm) is as follows:

$$\varepsilon = 0.083 \quad (\Delta \lambda) \tag{1}$$

The accuracy of the standard measurement apparatus is ± 32 pm, which is 0.003% of deformation.

The effect of the temperature was also studied. The relation between the temperature T (in °C) and the wavelength λ (in nm) is as follows:

$$\Delta \lambda = 0.0106\,(\Delta T) \tag{2}$$

A variation in temperature, $\Delta T = 10°C$, for a non-stressed fiber causes a displacement wavelength, $\Delta\lambda = 0.106$ nm, which would correspond to a deformation, $\Delta\varepsilon = 0.01\%$, at constant temperature. Temperature compensation is not generally required for sub-surface applications where the temperature variations are small in a majority of cases. However, it can be performed with a mechanically insulated sensor.

Sensors in a network

The response of several different sensors, or a "network of Bragg," can be measured simultaneously when placing several networks in series attached to one lead optical fiber. It is an important advantage of this technology as compared to traditional strain sensor measurement, which requires that each sensor be individually connected to the acquisition system. The significance is that by using different wavelengths that are reflected by the mirrors, various FBG sensor signals can be identified. The space-distributed sensors are identified and distinguished because each sensor has its own characteristic wavelength. The number of different FBG's will depend on the available bandwidth and on the amplitude of the shift expected for each FBG.

An optical switch must then be used to connect several optical fibers to the light source and the spectrometer that measures the reflected wavelengths. The switch makes possible to scan all the connected lines sequentially; see Figure 3. This configuration allows a spatial distribution of the sensors in a monitored structure to be read by only one measuring unit.

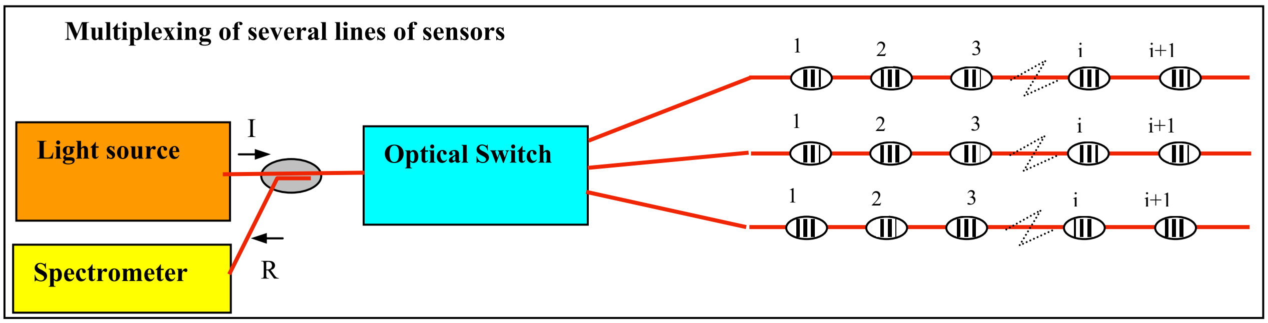


Figure 3. Diagram of a measurement system for optical fibers and FBGs.

The measurement system

The total Geodetect package is composed of a geosynthetic material in which optical fibers with FBG's are inserted, along with the data acquisition and analysis devices. The optical fibers are attached to the geosynthetic in the manufacturing phase of the reinforcement; see Figure 4. The result of having a measuring device directly integrated into the geosynthetic greatly simplifies implementation beyond what can be obtained with traditional sensors.

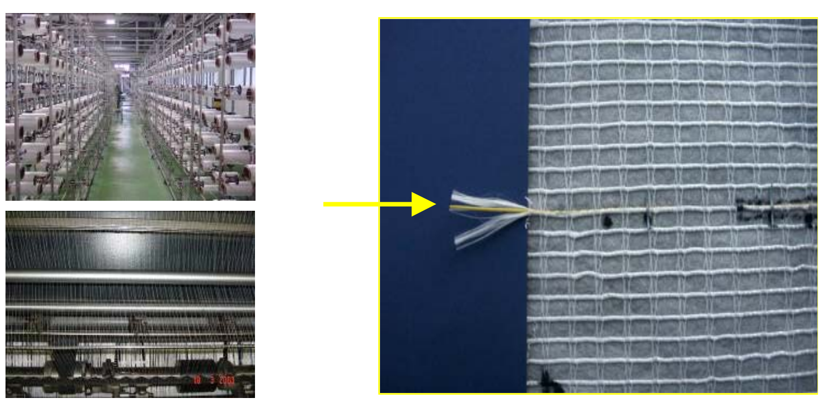


Figure 4. Optical fiber inserted during production.

The measurement devices consist of a data collection device (spectrometer) and a computer (or laptop) that allow the optical fibers to be spectrally analyzed. The spectrometer is available in a hand-held version that connects to a PDA for discrete sensor readings. This is an interesting solution for monitoring structures when the risk is too great for continuous sensor readings.

The "optic fiber" system properties

To ensure a water-tight monitoring device, a flexible sheath protects the optical fibers. Thanks to this sheathing and the intrinsic behavior of the fiber, the system has the following characteristics;

- immune to lightning strikes,
- corrosion resistant,
- free of electromagnetic interference,
- radiation resistant, and
- explosion proof (no risk of fire from sparks).

VALIDATION OF THE SYSTEM: TEST AND EXPERIMENTS

The Geodetect system was tested both in small scale in the laboratory and full scale in the field. The system's resistance to installation stresses and its practical performances were studied closely and validated. Production testing made it possible to establish a means of integrating the optical fibers into the geotextile within the range of the tolerable stress of the optical fibers.

Small scale tests in the laboratory

The results of the laboratory testing have been previously reported (Briançon, et al., 2004). The principal results are summarized below:

- Tensile tests made it possible to verify that the maximum deformation tolerated by optical fiber was in the range of the deformations which are generated in geosynthetic reinforcement in civil engineering applications.
- Damage tests made with a shear box were used to verify that the device could undergo loading without a loss of signal, or deterioration, when used with a coarse granular material.
- The deflection and membrane tests indicate good reproducibility of the measurements recorded by the FBG's, as well as the high sensitivity of the system.
- Measurements of deflection and deformation were compared with computed values obtained by a three dimensional FEM code that takes into account the fibrous nature of the geosynthetics.
- This laboratory analysis highlighted the limits of its testing since it was not possible to apply large loads representative of field conditions.
- The correlation between FBG sensor values and computed values were observed.

Full-scale tests at LRPC Nancy

Description of the different phases

In order to better investigate the performances of the system under field conditions, in particular its behavior during installation, during the compaction of soil material and during subsoil collapse, experiments were carried out at the Regional Laboratory of the Bridges and Roads of Nancy (LRPC Nancy).

The first phase took place in September 2002 and consisted of installing a geotextile equipped with two optical fibers 0.5 m apart with each one composed of thirty sensors with a spacing of 1m. Several levels of compaction were carried out to evaluate installation damage resistance; see Figure 5(a). Then, a local collapse of the sub-soil was simulated by deflating two balloons installed under the geotextile (Briançon, et al., 2004).

Figure 5(a). Damage test September 2002.

Figure 5(b). Loading test October 2003.

The second phase began in May 2003 and consisted of removing the balloons for a better visualization of the deformation in the Geotextile. Finally, the third phase began in October 2003 and consisted in loading using concrete blocks, on the surface of the ballast layer over the cavity to further observe the deformation of the geotextile; see Figure 5(b). In order to check the accuracy of the deformations registered by the FBG's, an INVAR wire and potentiometer system of measurement was installed.

Four sheathed rigid cable extensometers were affixed to both sides of the points to be measured and at the center of each air bag and coincident with the FBG sensor locations. The displacement of the extensometers makes it possible to evaluate the deformation by differences (Points P1 to P8 in Figure 6).

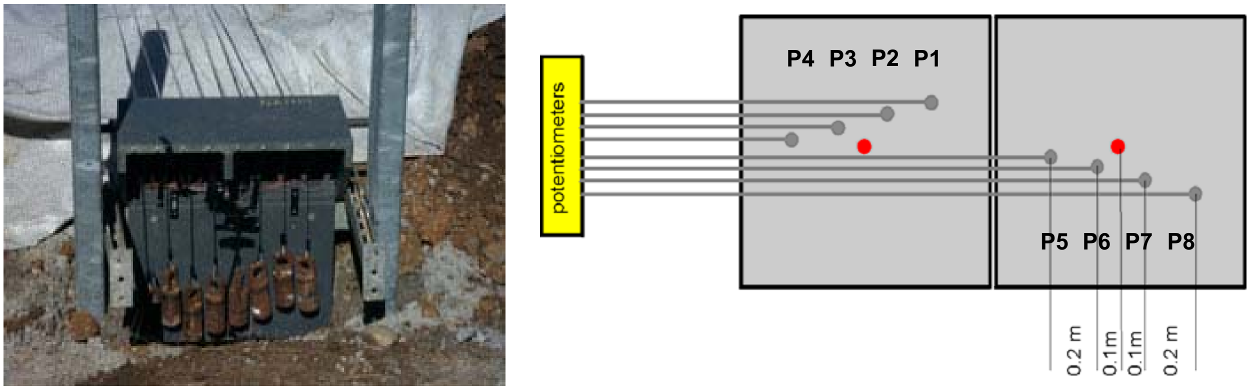


Figure 6. Measurement devices (extensometers) complementary to the Invar wire and potentiometers.

Results of measurements at the time of phased loading in October 2003

For each wire couple, one can calculate the deformation and compare it with the measurements taken by the FBG sensors. Table 1 shows the deformations obtained at each stage of the testing via the potentiometers.

Table 1 – Incremental deformations for each stage measured by the potentiometers

Action Taken	P1- P2	P2- P3	P3- P4	P1- P4	P5- P6	P6- P7	P7- P8	P5- P8
deflating	0.38%	0.21%	0.61%	0.40%	1.05%	0.50%	1.26%	0.94%
removal of the cushion	1.05%	0.16%	0.80%	0.67%	0.36%	0.84%	0.62%	0.61%
excavation	0.42%	0.17%	-0.35%	0.08%	0.23%	0.11%	0.62%	0.32%
loading 1	0.68%	0.32%	-0.17%	0.28%	0.19%	0.11%	0.33%	0.21%
loading 2	1.66%	0.52%	-0.25%	0.65%	0.77%	0.33%	0.28%	0.46%
loading 3	0.93%	0.47%	0.13%	0.51%	0.87%	0.56%	0.69%	0.71%
loading 4	0.46%	0.41%	0.26%	0.37%	0.49%	0.45%	0.52%	0.49%
loading 5	0.54%	0.39%	0.52%	0.48%	0.79%	1.02%	0.21%	0.67%

Comparison of optical measurements to the potentiometers

Figure 7 shows the correlation between measurements of the two FBG's sensors located at the top of the cavity and those measured with potentiometers for a gauge base of 60 cm. The correlation between the two measurement systems is very good with a low dispersion around the average curve. The points on the graph correspond to the deformations measured at the level of sensors FBG3 and FBG4, directly by the optical sensors and via the potentiometers.

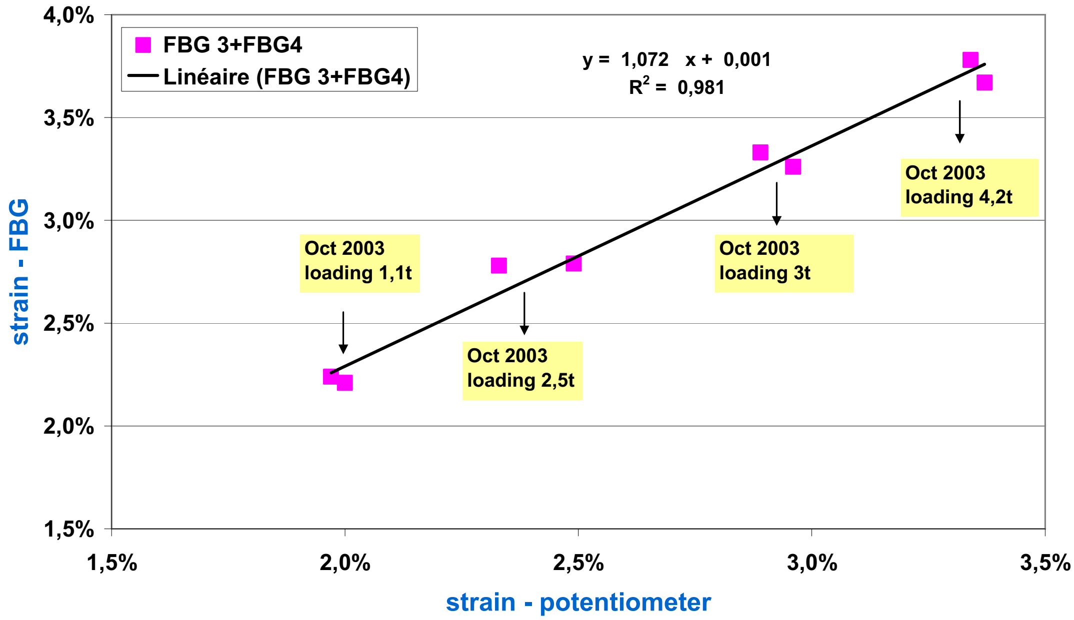


Figure 7. Comparison between measurements and potentiometers and those with optical fibers.

For each stage, the displacements measured by the potentiometers were re-initialized while the deformations of the FBG's are those accumulated since the installation. This helps to explain the shift at the beginning of the correlation curve. In Figure 8, the deformations calculated between the fixed points of the Invar wire and those measured by sensor FBG4 are represented which are visible until loading 3. The curve P5-P8 corresponds to the deformations calculated over an initial gauge length of 60 cm. The other curves show the deformations for a base measurement of 20 cm on the level of the FBG sensors (curve P6-P7) or on both sides (curves P5-P6 and P7-P8). A better correlation of values between sensor FBG4 with those from the potentiometers can be noticed for a base of measurement of 60cm and a larger difference between the point separated by 20 cm.

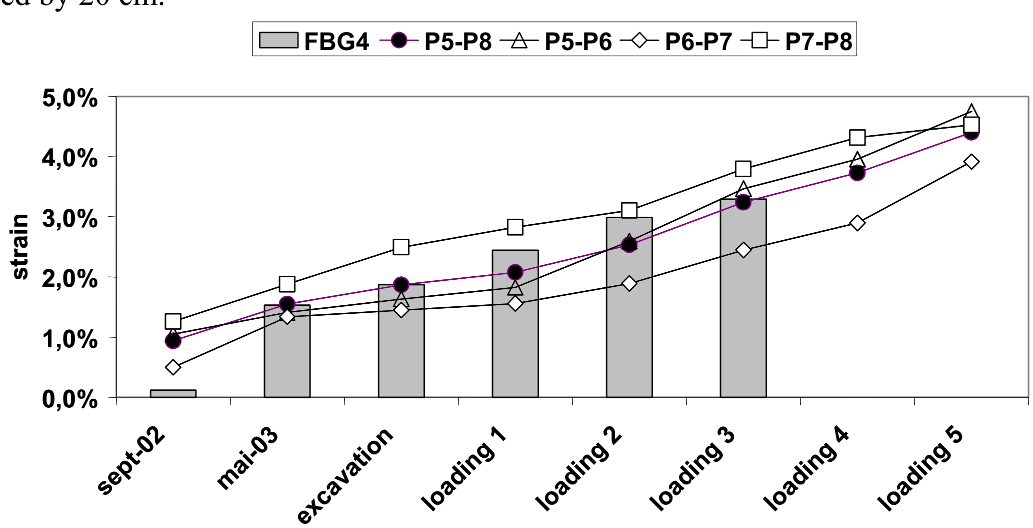


Figure 8. Comparison of measurements of sensor FBG4 and those from the potentiometers.

Durability

A study was begun (FOS&S 2006) to investigate the long term optical and mechanical performance of the fiber used in the Geodetect system when exposed to salt water. Accelerated aging tests have been performed on the optical fiber. The fibers have been submersed in three different basins (autoclaves) filled with salt water (containing 3.5% salt), with each basin at a different test temperature and test time i.e. 70, 80, and 90°C for each temperature a time-schedule of 112, 56, and 28 days, respectively.

The accelerated aging has been carried out at SKZ in Würzburg, Germany, during which some parameters such as FBG reflectivity, FBG wavelength and fiber attenuation have been measured in-situ. Other parameters such as mechanical strength, temperature, and strain sensitivity have also been analyzed.

Figure 9. Test set-up at SKZ: three autoclaves with optical fibers (filled with salt water and heated at 70°C,80°C and 90°C) respectively.

The following conclusions can be drawn from these experiments:

- The non-jacketed fiber shows a strong decrease of mechanical strength. However, the jacketed fiber only shows a slight decrease in tensile strength. It needs to be emphasized that the tested mechanical strength is the breaking tensile force on the fiber and does not take into account fatigue effects resulting from long term mechanical strain effects. This would require a completely different test set-up which falls outside the scope of this test program.

- No significant change in fiber attenuation and reflectivity stability could be observed due to aging for neither the jacketed, nor the unjacketed fiber.
- A small increase in wavelength was observed in the non jacketed fiber. The jacketed fiber did not show a significant ageing effect for this parameter.
- The temperature sensitivities of the FBGs show a slight decrease in the aging test.

Based on these test results, it can be concluded that jacketing is crucial to protect the optical fiber from the effects of salt water, and that the current jacket fulfils this function very well.

FEEDBACK ON THE EXPERIMENTS AND FIELD APPLICATIONS SINCE 2002

Experimental program of LRPC Nancy

After the various loading phases, the optical measurement system was left in the ground under the granular material. The state of the trench is presented Figure 10(a). At the time of the site visit in September 2005, it was observed that the fiber optic remained operational after three years installed the ground. The ground surface at the Nancy laboratory site, on which the experimental work was carried out, is close to the ground water table, which implies that the optical fiber equipped geotextile is regularly immersed in rainy periods. But this presence of water did not deteriorate the operation of the system. Figure 10(b) shows the pit filled with water where the loading took place.

	
(a) Condition of the trench and the measurement of control	(b) Geotextile spanning the top of the cavity

Figure 10. Control Test Sites in September 2005.

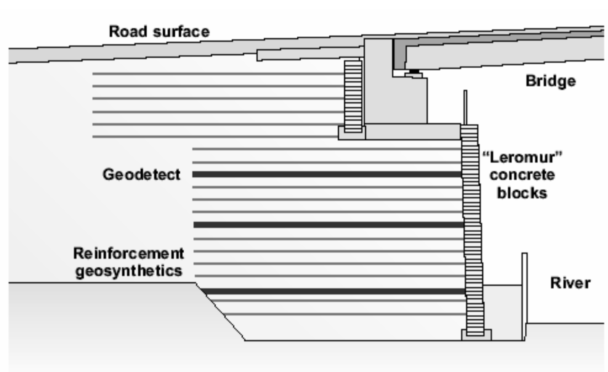
Instrumented projects

Several civil engineering projects were instrumented with the Geodetect system in Europe (Austria, France, Germany, UK), in Asia (Malaysia, Singapore), and in the United States. In France, geotextiles equipped with optical fibers with 300 sensors was installed under a railway in

October 2005 to detect subsidence under the tracks. This work is the subject of the paper in the 8th ICG in Yokohama (Briançon, et al., 2006).

The first full scale application of the Geodetect system in a civil engineering project was carried out for a retaining work in Saint Saturnin (France). This work (Nancey, et al., 2006), being a bridge abutment reinforced by geotextiles is shown in Figure 11.

Three bands that each contained a optical fiber with eight FBG sensors were installed in the soil fill during the construction of the wall in July 2004. A follow-up was carried out in June 2005, after the installation of the road structure on the top of the bridge. Figure 12 shows the change in the average deformation of one of the strips during 11 months of service.



(a) Cross section and placement of the strips (b) Installation of the system

Figure 11. Saint Saturnin MSE wall.

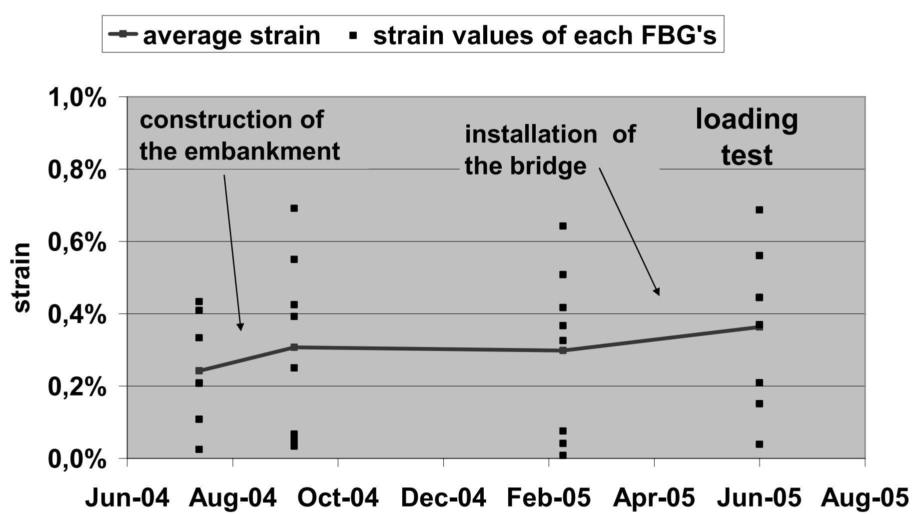


Figure 12. Evolution of deformation and the average between installation and completion of the bridge.

The deformation increased slightly during the construction of the wall between July 2004 and September 2004, and again between February and June 2005, the period during which the foundation and the bridge were installed. On the other hand, the deformations remain overall stable between September 2004 and February 2005, which is one period without activity. It is particularly interesting to note that the measured deformations are relatively small, with maximum values lower than 0.8%. However, they are on the same order as those recorded on other projects that were the subject of instrumentation studies, e.g., Bathurst, et al., (2002).

HOMELAND SECURITY

Based on the sensitivity and longevity of the Geodetect product, its use could be beneficial in many applications. These uses include, but are not limited to, the following.

1. Coastal/shoreline surveillance; beach landings of unauthorized vehicles, weight of boats and heavy equipment landing on shore.
2. Border surveillance; ground subsidence from tunneling activities, and subsequent subsurface subsidence.
3. Border surveillance; such as unauthorized vehicles crossing borders and vehicle load identification.
4. Inland waterway earthen dam and levee surveillance; such as embankment continuity and stability as well as degradation of embankment foundations or berms.
5. Military facility surveillance; such as breech of perimeter by unauthorized vehicles, and weight of vehicles or aircraft breaching perimeter or landing on airstrips.
6. Critical systems surveillance; such as breech of pipelines, utility conduits, asset delivery systems, rupture of pipes, conduits, etc.
7. Catastrophe intervention situations; such as large ground movements, discovery and monitoring of ground surface and near surface for large ground movements by events such as earthquakes and super volcanoes (Yellowstone).
8. Accident avoidance; for example, aircraft or ship structure overstress, discovery and monitoring of aircraft fuselage and wings, ship hulls and decks for structural overstress.

CONCLUSION

During the period of time after the initial Geodetect experiments of numerous sizes, the performance of instrumented geotextiles with FBG sensors were observed on several civil engineering projects. This tool is fast and easy to implement and makes it possible to observe the behavior of an application and to track its deformation over time. The deformations measured by this fiber optic technology were comparable with those obtained using conventional systems. Having a functional and accurate system of measurement that lasts more than a year after its installation on projects, and for more than three years on experimental applications illustrates the durability of this technique. Its durability goes well beyond that of traditional methods generally limited in life to a few months, knowing that in the ground the lifetime of the optical fibers with an adequate protection, can be estimated to be 20 to 30 years (resistance loss limited to 10%).

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