NEW TECHNOLOGY FOR STRAIN MEASUREMENTS IN SOIL AND THE SURVEY OF REINFORCED EARTH CONSTRUCTIONS

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ABSTRACT: The survey of civil engineering works and reinforced earth structures is more and more necessary either to detect the first sign of degradation before failure or to provide the designers/owners information on the behaviour of their structures . In the area of geosynthetics, such surveys have been requested mainly in the case of soil subsidence risk, relating to the quicker construction techniques available using appropriate geosynthetics. Until recently , only systems that should be installed by hand were available whatever the accuracy of the measurement. This made the survey of large areas difficult.
In this context, the “Geodetect” program was launched to develop a warning system using the advantages of optical technology inserted within a geosynthetic. The results of the development comprises a reinforcing geosynthetic equipped with optical fibres, which offers an accurate measurement system, available for very large areas, which is easy to install and includes an analysis device and warning system, which may be adapted to the clients needs.
This paper introduces the different steps of the validation including laboratory testing for fine tuning of the system, an experiment in the LRPC Nancy to show the resistance against damage during installation and the behaviour of the geodetect above a cavity.

1 INTRODUCTION

Construction of highways or railway lines requires a detection exercise of localised sinkholes in areas at risk. However, such cavities either cannot be detected or appear after the structure construction (e.g. karstic cavities). In area at risk, it is necessary to use reinforcement techniques; those with one or many geosynthetics could be especially interesting because it is easy to install and relatively inexpensive. A research test program concerning geosynthetic reinforcement solutions (RAFAEL), has already been carried out by a group of laboratories (Giraud 1997).

In spite of the reinforcement, a risk occasionally remains with respect to the development of the sinkhole toward the surface. To avoid failure the detection system must anticipate the first signs of any movement at the surface. Consequently, the efficiency of the reinforcement system could be improved by a warning system installed within the construction.

To solve this type of problem, Bidim Geosynthetics and ID-FOS launched the “Geodetect” program to develop a warning system based on optical technology inserted within a geosynthetic. An experimental program with laboratory tests and full-scale experiments was carried out to validate this new system performance.

2 EXISTING MONITORING SYSTEM

To establish a state of the art system in the localised sinkholes survey domain, various monitoring systems were investigated. They were classified in three groups:

- Usual sensors,
- Electric warning system,
- Ground Penetrating Radar.

2.1 *Usual sensors*

In this group, two kinds of sensor are distinguished: sensors fixed to the geosynthetic (to measure the strain) and sensors installed within the soil (to measure the settlement).

Various kinds of sensors could be fixed to the geosynthetic (Buonanno et al. 2000): strain gauge, rod extensometer and inclinometer. These sensors could be used only for punctual measures during a full-scale test for example. They cannot be used in a warning system because their lifetime in soil is short and they require a high degree of attention when installed on a geosynthetic.

Sensors in soil could not be used in a warning system. The use of settlement gauges requires a great deal of care to install correctly within the embankment. The Hydrostatic Profile Gauge could be used in a warning system in an area at risk with a length of a few hundred meters, but it could only detect the larger localised sinkholes.

2.2 *Electric warning system*

A warning system was tested in a test frame for a full-scale experiment for localised sinkholes detection (Ast and Haberland 2002, Leitner et al. 2002).

This device is constituted by a non-woven-signal-wire-matrix: two non-woven geotextiles are fitted together with electric wires in-between. With this newly developed composite, the deformation below the warning layer is indicated by the increase of electric resistance.

This device seems to be efficient for cavity detection. However, the electric aspect of this device is a major disadvantage for railway-line application (electrical interferences with systems of rail signs etc…).

2.3 *Ground Penetrating Radar*

Ground Penetrating Radar is a non-intrusive electromagnetic geophysical technique for subsurface exploration, characterization and monitoring. It is widely used in locating utilities, environmental site characterization and monitoring, unexploded ordnance and land mine detection, groundwater, pavement and infrastructure characterization (Simonin 2002), mining, void, cave and tunnel detection, sinkholes, subsidence, karst, and a host of other applications.

The application of such a device to the sinkholes survey is easy and requires the lay out of a wave reflective layer. However, this device requires:

- A daily detection and could be expensive,
- The traffic of vehicles above the cavity to detect it which could be hazardous.

3 THE NEW WARNING SYSTEM

In this context, the “Geodetect” program was launched to develop a warning system based on optical technology within a geosynthetic. This system has the advantage of combining reinforcement with an early warning system

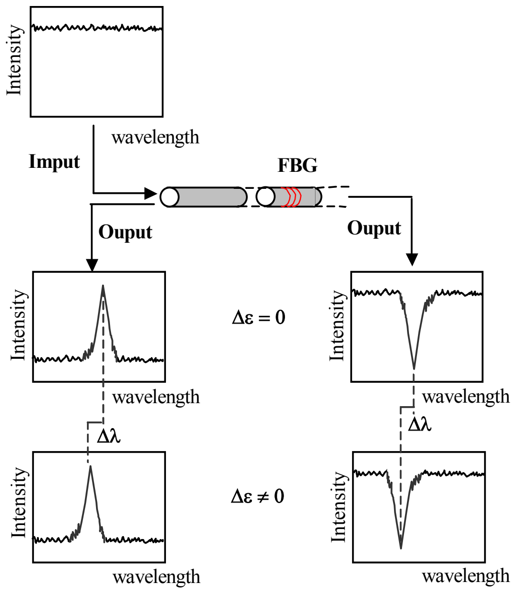

Fig.1 Fibre Bragg Grating principle

3.1 *The reinforcement geotextile*

The reinforcement geotextile is a ROCK PEC geotextile constituted by a non-woven and a PET reinforcement yarns. Yarns are needle punched to the non-woven in the main production direction.

3.2 *Optical technology*

The use of optical fibres for monitoring expanded in the 1980s. Various monitoring devices were developed. Our warning system uses the technique of the Fibre Bragg Gratings (FBGs).

Fibre Bragg Gratings (FBGs) are diffracting elements printed in the photosensitive core of a single mode optical fibre. This grating reflects a spectral peak based on the grating spacing, thus changes in the length of the fibre due to tension or compression will change the grating spacing and the wavelength of light that is reflected back. Quantitative strain measurements can be made by measuring the centre wavelength of the reflected spectral peak (Fig. 1).

The interest is that by using different wavelengths on which the mirrors are reflecting, signals of various FBG sensors can be identified. The wavelengths and wavelength-shifts of these so-called mirrors can be measured with a fibre optic unit allowing the demultiplexing of them in the wavelength domain. In this way, the space distributed sensors are identified and distinguished.

Because each sensor has its own characteristic wavelength, the sensors can be connected in series on one optical line or a star configuration can be made. In this way (by using an optical switch) several hundreds of sensors can be measured with a relatively small low cost interrogation unit.

3.3 *The “Geodetect” system*

Optical fibres are inserted inside the geotextile during the manufacturing process of inserting the reinforcement yarns (Fig. 2). As the warning system is directly inserted in the geotextile the installation problem often met with traditional sensors is overcome.

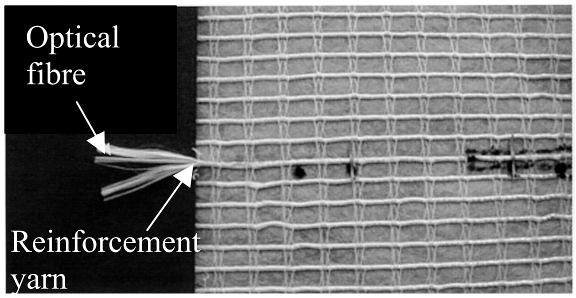

Fig.2 Geotextile with optical fibre inserted during the manufacturing process

To ensure the water-tightness of the monitoring device, a flexible sheath protects the optical fibres. Due to this sheathing over the optical fibres, the “Geodetect” system is:

- Immune to lightning strikes,
- Corrosion resistant,
- Free of electromagnetic,
- Radiation resistant,
- Explosion proof (no risk of sparks).

The measurement system consists of a data collection device (Geodetect FBG-Scan) and a computer/laptop allowing the assessment of the optical fibres spectral results. The Geodetect FBG-Scan is also available in a hand-held version connectable to a PDA for instantaneous checking on instrumental earthworks. This is an interesting solution for the follow-up of structures, when the risk cannot justify a continuous survey.

The “Geodetect” system was tested both in small scale in the laboratory and in full-scale. The resistance to the installation stresses and practical performances were especially studied and validated.

4 PREMILINARY TESTS

4.1 *Product test*

An optical fibre is linked to the geotextile directly in the assembly line. It is connected to a data collection device allowing assessment of the strain during all the production steps (i.e. inserting in the product line, needle-punching, rolling up). The result of this test highlighted that:

- The inserting step did not produce an increase of strain,
- During the needle-punching, strain increased until 83 με,
- During the rolling up, the strain did not exceed 124 με.

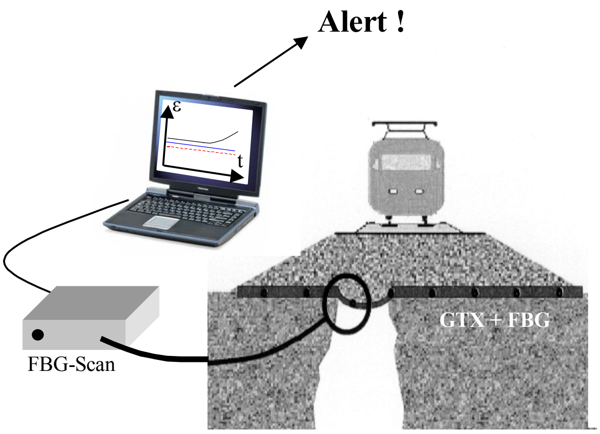

Fig. 3 The principle of the “Geodetect” system

4.2 *Strain tests*

Strain tests were performed on geotextile samples monitored by FBG. These tests met the specifications of the standard EN ISO 10319.

Samples were placed in the strain bench and stretched at a rate of 5 %/mn . A pre-load of 150 kN was applied. A series of charge / discharge were applied on the samples. These tests allowed checking that, before breaking, optical fibres could endure 6 % of strain applied to the geotextile.

4.3 *Conclusion about preliminary tests*

These preliminary tests allowed checking of the insertion process. The optical fibres are linked to the product during the manufacturing process guaranteeing a strong connection with the geotextile, resulting in a pertinent measure of the elongation.

Before breaking, the strain measured by the optical fibre is in the strain interval endured by the geotextile when it is used to reinforce earth structures.

5 DAMAGE TESTS

After the preliminary tests, the “Geodetect” system development consisted of checking the damage during installation. Two kinds of test were performed:

- Tests in shear box, to verify if the signal is not lost when the geotextile supports great stress,
- Full-scale test, to verify the product performances during its installation (discharge of soil above the geotextile, compaction …).

5.1 *Damage tests in shear box*

Two types of test were performed in a shear box:

- Load tests,
- Shear tests.

5.1.1 *Load tests (without shear)*

The geotextile instrumented by optical fibre (with a Bragg grating in the centre of the sample) was set up between the two half boxes filled up with crushed gravel. A charge / discharge test was carried out (Fig. 4).

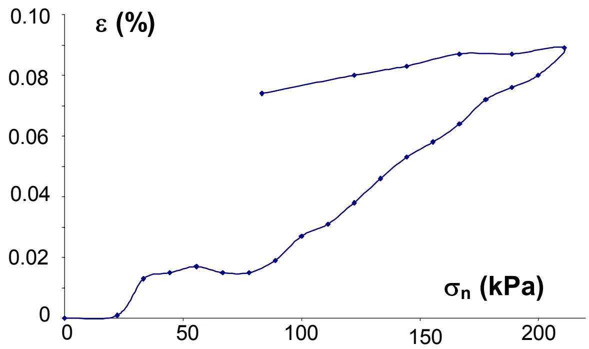

Fig.4 Strain measured by the FBG during the cycle of charge / discharge

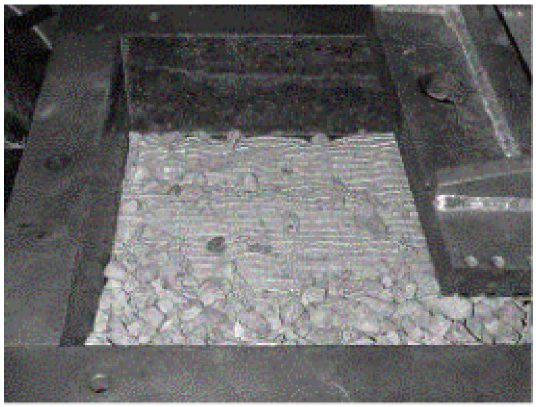

Fig. 5 Photo of the geotextile after the loading test

During the loading phase, strain increases linearly with normal stress; before 100 kPa, there is probably a new arrangement of the soil particles. Although the crushed gravel used is very damaging (fig. 5), the normal stress could be applied up to 200 kPa without loss of signal, nor deterioration of the system.

During the discharge, the strain decreases slowly to reach 0.07 % for a stress of 83.3 kPa; this slow reduction highlights the interlocking between the soil particles and the geotextile.

5.1.2 *Shear tests*

Following each test of charge / discharge, a shear test was performed with a normal stress equal to that applied at the end of the discharge.

Rupture was not reached for reasons specific to the equipment; however we noted that the strain did not increase during shearing. The application of a high normal stress during the loading test might have involved strong interlocking between the soil particles and the geotextile. Thus leading to occurrence of shearing in the soil itself, rather than at the interface between the soil and the geotextile.

5.2 *Damage tests during installation*

An experimental trench (30 m length and 2.5 m width) was delimited in 6 zones (LRPC site, Nancy, France). These zones correspond to a different protection level for the geotextile monitored by optical fibres.

The geotextile used is a reinforcement geotextile of 125 kN/m. It is monitored by two optical fibres 0.5 m apart. The cover soil (gravel 20/40mm) was set up in two 0.25 m thick layers (fig. 6). Compaction (fig. 7) was carried out using a type HAMM 2620D compactor proceeding in several phases (passes without vibration, with small vibrations and with large vibrations). The compaction controls, carried out by plate tests and Dynaplaque, validated a homogeneous compaction of the experimental trench.

Fig. 6 Installation of the soil cover

Measurements of strain were recorded throughout the various phases of the soil installation. The measured strains reached a maximum of 0.15 % during the soil installation with an average of 0.05 %. During a phase of intensive compaction (higher than the traditional compaction), there was rupture of an optical fibre. The rupture has been located under the area where the compactor stopped and turned round between two compaction phases.

Fig. 7 Soil cover compaction

On this zone, the sollicitation was extremely intensive and was applied during long time.

This full-scale experiment shows that, under normal conditions of set up, the “Geodetect” system is not damaged. However, in case of particular heavy compaction, a protection layer may be installed.

6 DETECTION TESTS

As with the damage tests, the detection tests proceeded in two phases:

- Laboratory tests with apparatus allowing measurement of the membrane effect,
- A full-scale test for which a localised sinkhole was simulated.

6.1 *Membrane effect tests*

The membrane effect tests were carried out on an experimental device of Lirigm (Fig. 8).

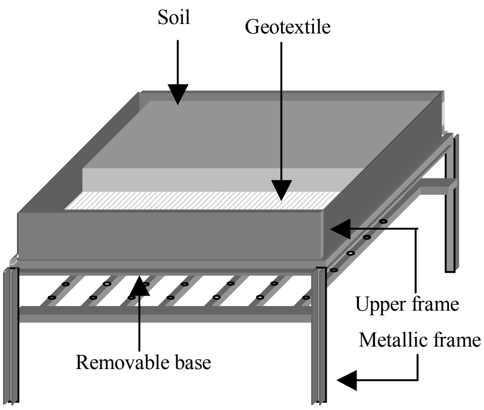

Fig. 8 Experimental device to measure the membrane effect

This device makes it possible to measure the membrane effect of a geotextile sample (1 m²). To measure the membrane effect, the geotextile is laid out between a removable base and a frame filled with soil The base is then removed. The geotextile used is a reinforcement geotextile of 125 kN/m. Two samples were tested. Each sample is monitored by a FBG:

- The Bragg grating is located in the middle for Sample 1,
- The Bragg grating is located 25 cm from the middle for Sample 2.

The simulation of a localised sinkhole for a rectangular cavity (1m x 1m) was carried out with both samples for a stress of 5 kPa; Three tests were performed for each sample. The simulation of a localised sinkhole for a circular cavity (Φ=0.9 m) was carried out with Sample 1 for a stress of 5 kPa. Sample 2 was used to measure the strain developed in the geotextile when it is laid out above a pile.

The results are only presented in the case of the circular cavity. Strain measured by Bragg grating is recorded during the test; a device on the metallic frame enables the measurement of the membrane’s deflexion.

The strains measured by Bragg grating during both tests are similar (Fig. 9).

Following test 2, an overload was applied in the middle of the upper frame. This overload involved an increase in the measured strain. When the overload was removed, the strain decreased but did not reduce to the level reached following the collapse. This observation highlights the formation of structural vaults in the soil.

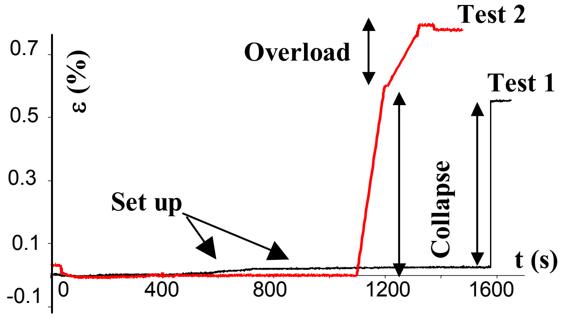

Fig.9 Strain measured for the simulation of a localised sinkhole for a circular cavity

The compatibility of the theoretical results with the measurements (geotextile deformation and strain measurements) was analysed using a three-dimensional finite element model of a circular sheet subject to a load distributed normal to its initial plane, following a method described by Villard and Giraud (1998). This model has been already validated by other studies (Villard et al. 2000).

The compatibility of calculated and measured displacements is great. On the other hand, there is little difference between the strain measured by Bragg grating and those numerically calculated. This difference can be allotted for an arching effect developed in the ground not taken into account in the model; indeed when the arching effect is disturbed by the application and the removal of an overload, the measured strain agrees with the numerically calculated strain.

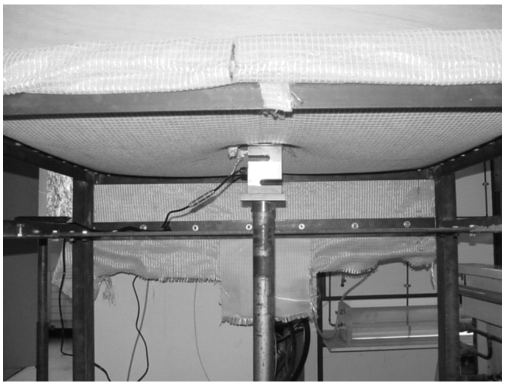

Fig. 10 Device configuration in the case when the geotextile is laid out above pile

The other configurations tested: rectangular cavity and geotextile laid out above pile (fig. 10), give results similar to those obtained with the configuration of the circular cavity. As a whole, there is a good correlation of the measurements transmitted by the Bragg grating and good agreement with the numerical model. The differences can be allotted to the formation of vaults in the ground and to the over emphasised stiffness of geotextile used for laboratory tests.

6.2 *Localised sinkhole simulation*

Two zones of the experimental trench of the LRPC site (Nancy, France) were especially prepared for the simulation of a localised collapse carried out by the deflating of two balloons located under the monitored geotextile (Fig. 11).

Fig. 11a Fig. 11b

Fig. 11 (a) balloons set up - (b) survey of surface settlement

During deflating, the Bragg gratings located above the cavity indicated an increase in strain instantaneously. The increase in strain generated by the passage of a vehicle above the cavity was also identified by the Bragg gratings. On the other hand, a difference between the recorded strains and the calculated values was noted. This difference could be allotted to a partial deflating of the balloons. This assumption was confirmed by the lower settlements measured on the surface.

To supplement this experimentation of detection of a localised collapse, an investigation was carried out eight months later; comprising:

- checking the medium-term behaviour of the warning system,
- verifying the surface settlement,
- removing the balloons in order to raise uncertainties on a possible reaction under the geotextile.

Measurements of strain transmitted by the Bragg gratings indicated an increase for those Bragg gratings located in the cavity zone (above the cavity and at the edge of the cavity). There is also an increase for three Bragg gratings within the adjacent zone of the cavity. These observations indicate that there undoubtedly was a slow deflating of the balloons at the time of the first experimentation.

The measurement of the surface settlement (Fig. 11b) validated the strain increase of the geotextile.

An adjacent trench was dug beside the experimental trench at the level of the balloons. When the balloons were found, we observed that a large quantity of gravels were located between the balloons and the geotextile, confirming the assumption of a reaction under the geotextile.

When the balloons were removed, they were completely deflated. The access to the cavity was widened in order to reach under the geotextile and carry out deformation measurements (fig. 12).

Fig. 12 Geotextile deformation after the extraction of the balloons

During all stages of balloon removal, the measurements of strain transmitted by the Bragg gratings were recorded. An increase in the strain for all the Bragg gratings located in the cavity area and for three Bragg grating located in the zone at the edge of the cavity was observed. These observations indicate a relative slip of the optical fibre in its sheath (in the short or the long term), and thus the strain generated by collapse is measured over a length higher than the diameter of the cavity. This diffusion of the strain along the optical fibre must be taken into account in the case of a non continuous survey.

Because of the difference of stiffness of the optic fibre and the slip of the fibre in the sheath, the local strain of the optical line do not correspond exactly to the local strain of the geotextile, but the total extension remains the same. That has the advantage of limiting the deformations of fibre and of providing a measurement of extension, even in the case of local strains of geotextile higher than the permissible strain of FBG. This results in calculation of the extension of the optical fibre, by integrating the strains over the length of the fibre. If the deformation is integrated over the length of the deformed fibre, the extension obtained in the case of the Nancy experiment is 5.8 cm in the area where the Bragg gratings reacted. The elongation of the geotextile, calculated with the assumption of symmetrical deformation and for the average arrow of 20.5 cm, is 3 % for the 2 metres of the cavity then 6 cm of elongation (with the assumption of perfect anchorage of the geotextile).

The optical measurement of the elongation is very closed to the calculated value starting from the arrow. Some small differences could come from uncertainties on sizes of the cavity and from the variation between real and theoretical deformation.

7 CONCLUSION

The warning system by FBGs inserted to a geotextile developed by Bidim geosynthetics and ID-FOS was the subject of a research test program aiming towards its validation.

Integration tests of optical fibres confirmed the feasibility of the process. Strain tests highlighted that optical fibres could endure up to 5-6 % strain applied to the geotextile. Damage tests with the shear box confirmed the warning system performed even under great stress.

The warning system was tested at the time of its installation under severe conditions of compaction and under an aggressive material. This full-scale experiment highlighted that the system could support normal conditions of installation.

Laboratory membrane tests and a full-scale collapse simulation checked the performances of the warning system.

All the tests carried out made it possible to validate the performances of the warning system. Consequently, this new device and "intelligent" geotextile is fully operational for soil subsidence.

Future investigations are considered, in particular to further determine the amount of local strain and to provide further evidence allowing solutions to the various problems with respect to reinforcement and survey measurements.

8 ACKNOWLEDGMENTS

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