*Studia Geotechnica et Mechanica, Vol. XXVII, No. 1–2, 2005*

# DEVELOPMENT OF GEODETECT: A NEW WARNING SYSTEM FOR THE SURVEY OF REINFORCED EARTH CONSTRUCTIONS

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**Abstract**: Survey of civil engineering works and reinforced earth structures are more and more necessary either to detect the first sign of degradation before failure or to provide the designers and owners with some information on the behaviour of their buildings. In this context, the program "Geodetect" was launched to develop a warning system based on the optical technology applied in a geosynthetic.

The results of the development lead to a reinforcing geosynthetic equipped with optical fibres, offering an accurate measuring system, available for very large areas, easy to install and completed with an analysis device and a warning system which may be adapted to the client's needs.

This paper will present the different steps of the validation: tests in laboratory for fine tuning of the system, a full-scale experiment to show the resistance against the damage during installation and the behaviour above a cavity and a finite element modelling.

## 1. INTRODUCTION

Construction of highways or railways lines requires a detection campaign of localized sinkholes in areas at risk. However, such cavities cannot be detected or appear after the structure construction (karstic cavities). In area at risk, it is necessary to use reinforcement techniques; those with one or many geosynthetics could be interesting because it is easy to settle and inexpensive. A research program testing geosynthetic reinforcement solution was already carried out by a group of laboratories [1], [2].

In spite of this reinforcement, there is sometime a development of the sinkhole towards the surface. To avoid accident, the detection must anticipate the first signs at the surface and thus the efficacy of the reinforcement system could be improved by a warning system installed below the construction. To cope with this type of problems, Bidim Geosynthetics and ID-FOS launched the "Geodetect" program to develop a warning system based on the optical technology applied in a geosynthetic. An experimental program with laboratory tests and full-scale experiments and a numerical model were carried out to validate the performances of this new system.

## 2. EXISTING MONITORING SYSTEM

To establish the state-of-the-art in the survey domain of localized sinkholes, various monitoring systems were investigated. They were inventoried and divided into three groups:

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

### 2.1. USUAL SENSORS

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

Various kinds of sensors could be fixed to the geosynthetic [3]: strain gauge, rod extensometer and inclinometer. These sensors could be used only for punctual measures during full-scale test, for example. They cannot be used in warning system because their lifetime in soil is short and they require a lot of attention to be installed on the geosynthetic.

The use of sensor lost in soil (settlement gauges) requires a great care to install the embankment and such a sensor cannot be used in warning system.

### 2.2. ELECTRIC WARNING SYSTEM

A warning system was tested in a full-scale experiment allowing detection of the localized sinkholes [4], [5]. This device is made of a non-woven-signal-wire-matrix: two non-woven geotextiles are fitted together with electric wires at the inner side. With this newly developed composite, the deformations below the warning layer are indicated by an increase in electric resistance. This device seems to be efficient for the detection of cavities. However, an electric aspect of this device is its major disadvantage for its application in railway lines (electrical interference with systems of rail signs…).

### 2.3. GROUND PENETRATING RADAR

Ground Penetrating Radar is a non-invasive electromagnetic geophysical technique used for subsurface exploration, characterization and monitoring. It is widely used in locating lost utilities, environmental site characterization and monitoring, unexploded ordnance and land-mine detection, groundwater, pavement and infrastructure characterization [6], mining, void, cave and tunnel detection, sinkholes, subsidence, karst, and a host of other applications.

The application of such a device to the sinkhole survey is easy and requires the laying out a wave-reflecting layer. However, this device requires:

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

## 3. THE NEW WARNING SYSTEM

In this context, the "Geodetect" program was launched to develop a warning system based on the optical technology applied in a geosynthetic. This system combines the reinforcement aspect with the warning aspect.

### 3.1. THE REINFORCEMENT GEOSYNTHETIC

The reinforcement geosynthetic is a ROCK PEC geotextile made of a non-woven textile and the PET-reinforcement wires. Wires are needle-punched to the non-woven textilke in the production direction.

### 3.2. OPTICAL TECHNOLOGY

The use of optical fibres for monitoring expanded in the eighties. Various monitoring devices were developed. Our warning system uses the technique of the Fibre Bragg Gratings (FBGs). Fibre Bragg Gratings 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 the 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. Quantitative strain measurements can be made by measuring the centre wavelength of the reflected spectral peak. The interest is that by using different wavelengths reflected by the mirrors, 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 demultiplexing 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 low-cost interrogation unit.

### 3.3. THE “GEODETECT” SYSTEM

Optical fibres are inserted into the geotextile during the industrial process of reinforcement wires insertion (figure 1a). The warning system (figure 1b) directly inserted into the geotextile copes with the installation problem met with traditional sensors.

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

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

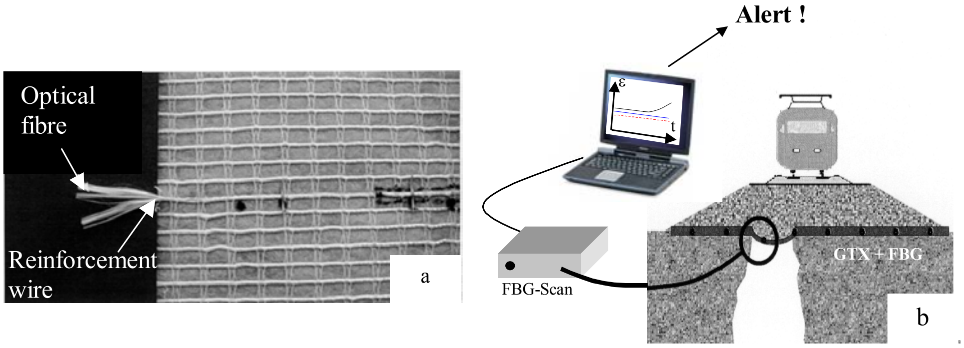

Fig. 1. The “Geodetect” system

The measuring system consists of data-collection device (Geodetect FBG-Scan) and of a computer (or laptop) allowing one to follow the spectral answer of optical fibres. The Geodetect FBG-Scan is also available in a hand-held version connectable to a PDA for punctual checking of instrumental earthworks. This is an interesting solution for the follow-up to structures, when the risk cannot justify a continuous survey. The “Geodetect” system was tested both in a small scale in the laboratory and in a full scale. The resistance to the installation stresses and practical performances were especially studied and validated.

## 4. LABORATORY TESTS

Various laboratory tests were carried out. They are as follows:

- Product test.
- Strain tests.
- Damage tests in shear box.
- Membrane effect tests.

BRIANÇON et al. [7] gave a detailed description of these tests whose main results are presented in this paper. The product tests allowed checking the insertion process. The optical fibres were linked to the product following industrial process guaranteeing a strong connection with the geotextile, resulting in a pertinent measure of the elongation. The strain tests showed that, before breaking, the strain measure by optical fibre was in the strain interval endured by the geotextile when it is used to reinforce earth structures. The damage tests in shear box allowed checking that great charge could be applied to the instrumented geosynthetic without loss of signal and deterioration of the system, although the crushed gravel used was very damaging. The membrane-effect tests were carried out for rectangular cavities, circular cavities and piled embankment simulation; they showed a good repeatability of the measurements transmitted by the Bragg grating and their good agreement with a numerical model, i.e. a three-dimensional finite-element model of a sheet subject to a load distributed normally to its initial plane, following a method described by VILLARD and GIRAUD [8]. This study highlighted the laboratory test limits of the stress applied.

## 5. FULL-SCALE TESTS

To validate the laboratory test results, a full-scale experiment was carried out. It allowed us to check the damage during the soil installation and the performance of cavity detection.

### 5.1. DAMAGE DURING THE SOIL INSTALLATION

An experimental trench (30 m length and 2.5 m width) was divided into 6 zones. These zones correspond to a different protection level of the geotextile monitored by optical fibres. The geotextile used was a reinforcement geotextile of failure tension of 125 kN/m; two optical fibres 0.5 m apart monitored it. The cover soil (gravel 20/40) was set up in two 0.25 m thick layers (figure 2a). The compaction (figure 2b), carried out using a tire compactor of the HAMM 2620D type, proceeded in several phases (passes without vibration, with small and great vibrations). The compaction control, carried out by plate tests and Dynaplaque, validated a homogeneous compaction of the experimental trench. Measurements of strain were recorded throughout the various phases of the soil installation. The strains measured approached to the maximum of 0.15% during the soil discharge but they were on average equal to 0.05%. During a phase of intensive compaction (definitely higher than the traditional compaction), the 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; in this zone, the solicitation was extremely intensive and was applied during long time. This full-scale experiment showed that under normal conditions of set up the "Geodetect" system was not damaged. However, in case of particularly heavy compaction, a protection layer may be installed.

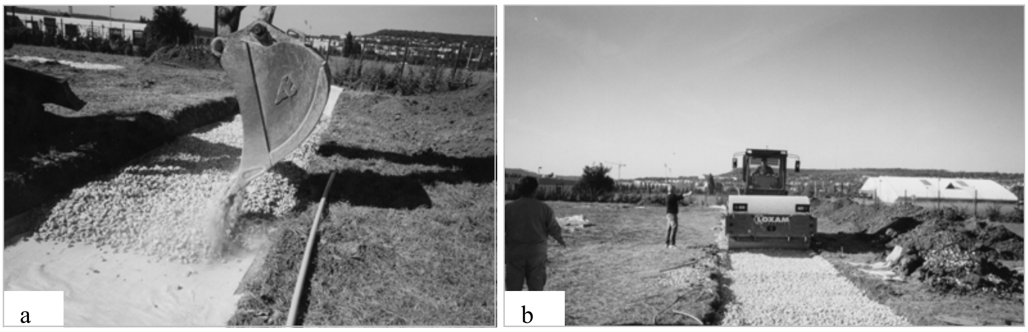

Fig. 2. Full-scale damage tests

### 5.2. SIMULATION OF THE LOCALIZED SINKHOLES

Simulation of the localized sinkholes was carried out in three stages:

- Measurements after deflating the balloons (the first experiment).
- Measurements after removing the balloons (the second experiment).
- Measurements during the cover soil loading above the cavity (the third experiment).

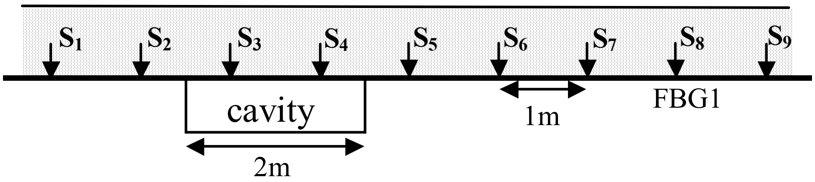

Fig. 3. Localisation of the Bragg gratings

*Deflating the balloons*. Two zones of the experimental trench were especially prepared for the simulation of a localized collapse (figure 3) carried out by the deflating two balloons under the monitored geosynthetic (figure 4a). During deflating, the

Bragg gratings above the cavity indicated instantaneously an increase in strain (the table, $\varepsilon_1$). The Bragg gratings also identified an increase in strain generated by the passage of a vehicle above the cavity (the table, $\varepsilon_2$). On the other hand, a difference between the recorded and the calculated values of strains was noted. This difference could stem from a partial deflating of the balloons. This assumption was confirmed by the weak settlements measured on the surface.

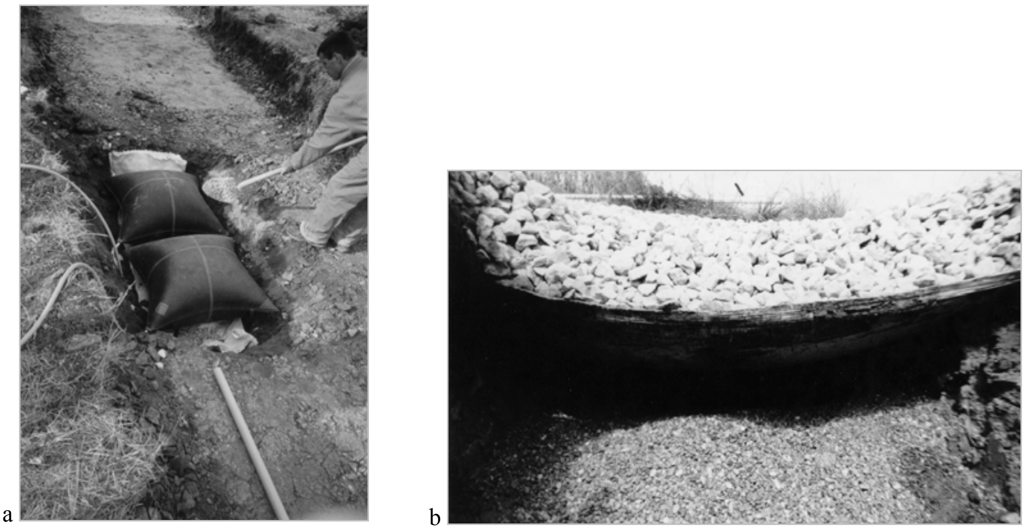

Fig. 4. Simulation of localized sinkholes

*Removing the balloons*. In order to supplement this experiment of detection of a localized collapse, an investigation was carried out eight months later; it consisted in:

- Checking the medium-term behaviour of the warning system.
- Verifying the surface settlement.
- Removing the balloons (figure 4b) in order to icrease uncertainties about a possible reaction under the geotextile.

Eight months after the first experiment, there was no problem to measure the strain with the Bragg gratings. The measurement (the table, $\varepsilon_3$) indicated an increase in the Bragg gratings located in the cavity zone (above the cavity and at the edge of the cavity), there was also an increase in three Bragg gratings of the zone adjacent to the cavity. These observations revealed that a slow deflating of the balloons occurred undoubtedly at the time of the first experiment.

Measurements of strain transmitted by the Bragg gratings during the various stages (the table) highlighted a symmetrical strain due to geosynthetic put on the cavity (sensors $S_3$ and $S_4$). The strain measured by the Bragg gratings $S_1$ and $S_2$ is smaller than the strain of measured by the Bragg gratings $S_5$ and $S_6$, because there was a wiremeasuring device (at the side of sensors $S_1$ and $S_2$) that made the geosynthetic rigid, and the anchorage at the side of the sensors $S_1$ and $S_2$ was only 2 m long.

After removing the balloons, there was a significant increase in geosynthetic strain above the cavity and in the anchorage area (the table, $\varepsilon_4$). The measurements of the surface settlement validated the strain increase in the geotextile.

A single analytic model [1] calculates the geosynthetic strain above the cavity, assuming that there is no displacement at both sides of the cavity. As the Bragg gratings localized at both sides of the cavity indicated an increase in the strain, it seemed necessary to use a numerical model able to simulate the interaction between the soil and the geosynthetic in the anchorage area. The numerical model used is a finite-element code formulated in conditions of great displacements, specifically developed to model the three-dimensional membrane behaviour of the geosynthetic sheet [8]. The specificities of the code lie in its capacity to take into account the fibrous structure of the geosynthetics. Each direction of fibre can be taken into account which makes it possible to model any type of geosynthetic (non-woven geosynthetic with fibres distributed uniformly in the plane, or woven geotextile reinforced in one or more directions).

Table

Strain measured by the Bragg gratings

| | The first experiment | | The second experiment | | The third experiment | | |
|---|---|---|---|---|---|---|---|
| Bragg gratings | Deflating the balloons $\varepsilon_1$ (%) | Passage of a vehicle $\varepsilon_2$ (%) | Start $\varepsilon_3$ (%) | Removing the balloons $\varepsilon_4$ (%) | Start $\varepsilon_5$ (%) | Loading of 5.3 kPa $\varepsilon_6$ (%) | Loading of 12.4 kPa $\varepsilon_7$ (%) |
| S1 | 0.01 | 0.00 | 0.11 | 0.12 | 0.32 | – | 0.58 |
| S2 | 0.02 | 0.05 | 0.69 | 0.99 | 1.51 | 1.91 | 1.98 |
| S3 | – | 0.23 | 0.91 | 1.50 | 1.87 | 2.42 | 2.89 |
| S4 | 0.11 | 0.12 | – | 1.53 | 1.87 | 2.44 | 2.99 |
| S5 | 0.04 | 0.09 | 0.74 | 1.07 | 1.51 | 1.78 | 2.26 |
| S6 | – | – | 0.21 | 0.50 | 0.69 | 0.80 | 1.20 |
| S7 | 0.05 | 0.05 | 0.06 | 0.06 | – | – | 0.09 |
| S8 | 0 | 0 | 0 | 0 | 0.03 | 0.03 | 0.06 |

In the anchorage area, friction between soil and geotextile was taken into account. The Mohr–Coulomb law is considered for each friction interface ($\Phi_{\text{upper}} = 30°$ and $\Phi_{\text{lower}} = 25°$) assuming that friction is fully mobilised for a relative displacement of 5 mm. The stiffness $J$ of the geosynthetic is equal to 1100 kN/m. The elastic modulus of the soil $E$ reaches 30 MPa; this soil is modelled by vertical springs.

Comparison of the strain values measured by the Bragg gratings (after removing the balloons) with the numerical values (figure 5) highlights their broad agreement, provided that a geosynthetic strain occurs in the anchorage area. Accepting this assumption, we can state the calculated and measured values of vertical displacement of geosynthetic above the cavity are highly correlated (figure 6). This study shows that the assumption of no displacement of geosynthetic at both sides of the cavity is not realistic.

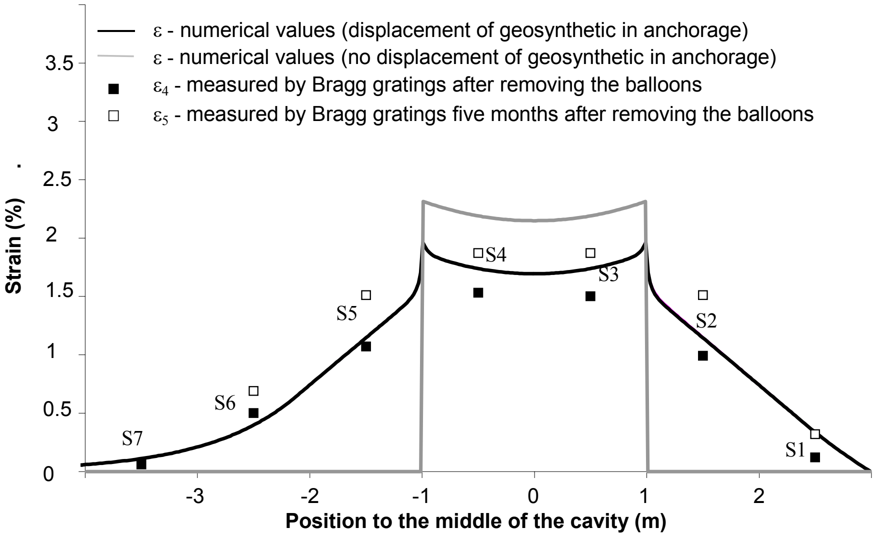

Fig. 5. Comparison of geosynthetic strain calculated and measured by the Bragg gratings

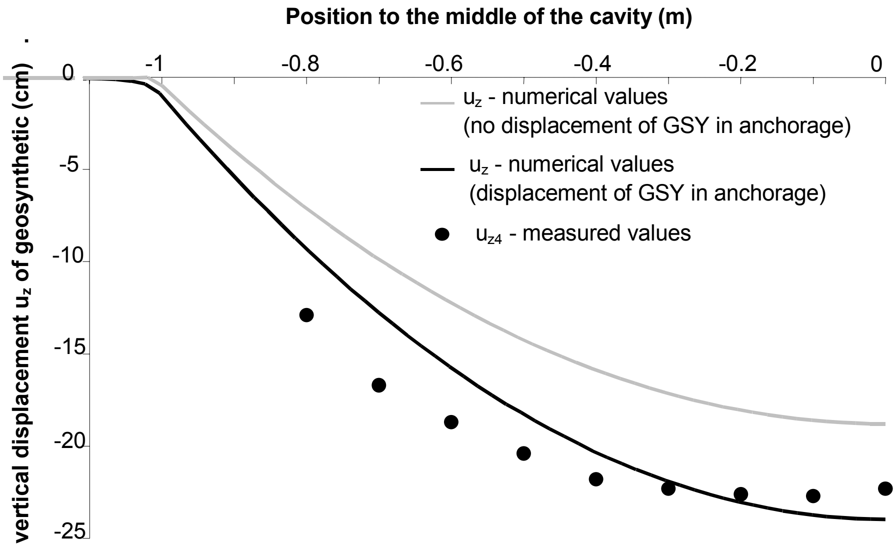

Fig. 6. Comparison of geosynthetic vertical displacement calculated and measured

*Loading above cavity*. To complete this experiment and to compare the measurements by the Bragg gratings with the numerical values in other cases, a load of 5.3 kPa and a load of 12.4 kPa were applied to the soil cover above cavity. This experiment was carried out five months after removing the balloons. For these tests, there was no measurement of geosynthetic vertical displacement but only the measurement of strain recorded by the Bragg gratings (the table, $\varepsilon_5$, $\varepsilon_6$, $\varepsilon_7$).

As the anchorage at the side of the sensors $S_1$ and $S_2$ was only 2 m long, a load was put in this anchorage area to avoid the slipping of the geosynthetic.

Five months after removing the balloons, a slight increase in geosynthetic strain above cavity and in the anchorage area was noticed (figure 5). In fact, the activation of the friction in the anchorage area is slow and the total strain of the system for a given load is not immediate. In spite of this difference, the numerical values (taking into account the displacement in the anchorage) are yet agreed with the measurements by the Bragg gratings.

In the cases where the cover soil has been loaded with various charges, there is also a broad agreement between the measurements by the Bragg gratings and the numerical values (figure 7). At the loading of 12.4 kPa, the values measured are less than these calculated above the cavity, but as we have already seen, the mechanisms of strain and displacement in anchorage area require time to be fully developed. Because of seting up the load in the anchorage area located at the side of the Bragg gratings $S_1$ and $S_2$, the strain measured by the Bragg gratings $S_1$ and $S_2$ is smaller than the strain measured by the Bragg gratings $S_5$ and $S_6$.

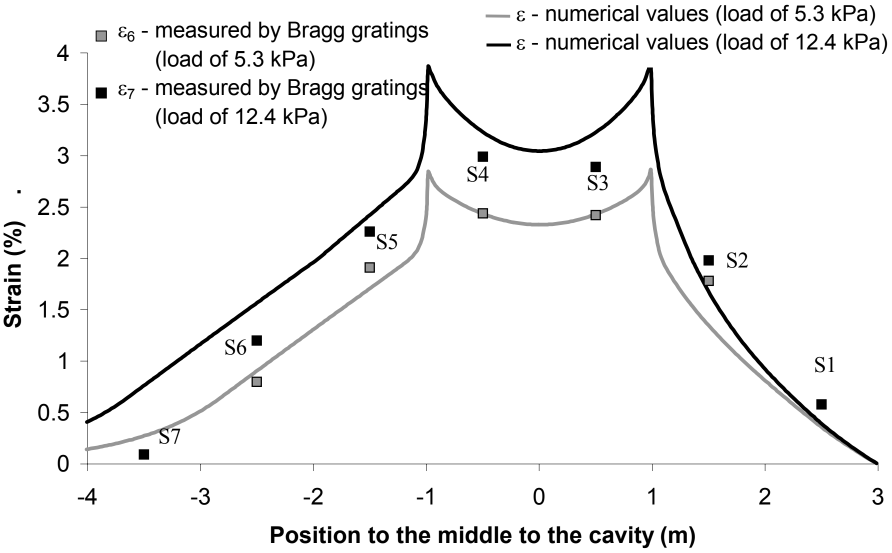

Fig. 7. Comparison of geosynthetic strain calculated and measured for the load experiment

## 6. CONCLUSION

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

Integration tests of optical fibres confirmed the feasibility of the process. Strain tests highlighted in this article revealed that optical fibres could endure up to 6% of strain applied to the geotextile. Damage tests carried out on the shear box confirmed a good behaviour of the warning system 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 the finding that the system could cope with normal conditions of installation. Laboratory membrane tests and a full-scale collapse simulation checked the performances of the warning system and showed the interest of using FBG technique to measure geosynthetic strain without difficulty, often met with traditional sensors, and with a great accuracy. The comparison between the measurements by the Bragg gratings and the values calculated with a numerical model highlighted their great agreement assuming a geosynthetic strain in the anchorage area and validated the monitoring method.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge ID-FOS who contributed to this project bringing their knowledge in the optical domain, the LRPC laboratory of Nancy for its participation in the full-scale experiment, the DRAST (French Ministry of Equipment) and the National Agency for the Valorisation of Research in the French Ministry of Industry who provided the necessary funds to sponsor this research.

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