Six years earthworks monitoring with a fibre optics geotextile enabled sensor

Olivier Artières, Gerrit Dortland

TenCate Geosynthetics, France

1 Introduction

Strain monitoring of earthworks with local sensors is an issue as they are difficult to install and have sometimes liability problems on the long term.

To solve these problems, a new solution has been developed at the beginning of the years 2000. It is based on a textile composite and fiber optics sensors using different technologies on optical fibers, to measure parameters such as soil temperature and strain,

The main advantages of this solution are the high measurement sensitivity, resp. 0.1°C for temperature and 0.01% for strain, the spatial resolution of about 1 meter, the durability of the sensors into the soil, the ability to monitor both small size works, such as slopes and walls, and very long linear infrastructures of several tenths of kilometers, such as roads, railways, dikes or pipelines.

The first projects were installed in 2004, either as a periodic monitoring solution of a bridge abutment reinforced with geotextiles in Le Mans (France) or as a continuous warning system on a railways section crossing a risky area with possible underground cavities in Arbois (France). The long term behavior of the monitoring solution after seven years of use is part of this paper.

This monitoring solution has also been installed in hydraulic works, such as dikes, levees and basins, to detect and localize the early signs of work malfunctioning, either instability or leakage. Finally an application in landfills is presented whose purpose is the soil strain measurement on top of a geomembrane capping liner.

2 The monitoring and early warning TenCate GeoDetect® solution

This solution has been developed within two Eureka European R&D projects Σ!2579 and Σ!3361. It combines a geotextile structure, optical cables (Figure 1), one optical instrumentation and the software to offer a very innovative solution for the multifunctional needs of geotechnical applications.

2.1 The sensor

The geotextile part brings on one side its mechanical and hydraulic functions, specially the high friction with soil, but also the common geotextile functions, for example in-the-plane drainage waterflow capacity, soil reinforcement or filtration. The geotextile also protects the optical cables and allows carrying several optical lines onto the same strip.

The optical fibers measure two main parameters for earth and hydraulic works monitoring which are soil strain and temperature. Soil strain measurement is possible due to on one side the high friction properties between the nonwoven compound of the geotextile structure and the soil, and on the other side the strong link of the optical cable on the textile. Soil strain is immediately transferred to the optical sensors.

Temperature measurement is useful for structural health monitoring, especially to assess frost/thaw cycles. It is also indirectly used to detect and localize leakage through dikes and dams for example. It is also used to compensate strain measurement from thermal variations.

The sensor is waterproof as the optical fibers are coated with several polymer protecting layers. With this coating and the intrinsic properties of the optical lines, the sensor is corrosion, lightning and radiations resistant. It cannot generate electromagnetic interferences, nor explosion (no risk of spark).

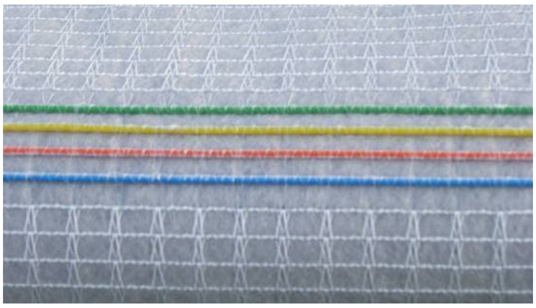

Figure 1. The textile composite sensor and the optical cables (colored).

2.2 The optical instrumentation

Fiber Bragg Gratings and Brillouin or Raman distributed scattering are proved measurement technologies with optical fibers that can be combined with this fiber optics monitoring solution.

2.2.1 Fiber Bragg Gratings

A Fiber Bragg Grating (FBG) is a local optical change inserted at a given and chosen point of the optical fiber. It is built with a series of close fringes written inside the core of this optical fiber (that can be seen as mirrors) whose refraction index is known. Each FBG reflects a narrow wavelength of the light beam and transmits the remaining part of the light spectrum.

The optical interrogator sends a wide light spectrum into the fiber; each FBG is identified by an accurate wavelength which is reflected (Figure 2a); this line ray corresponds to the nominal wavelength λ of the Fiber Bragg Grating. The reflected wavelength varies with the optical fiber temperature and strain. It is therefore possible to measure strain and temperature changes around the optical fibers (Figure 2b).

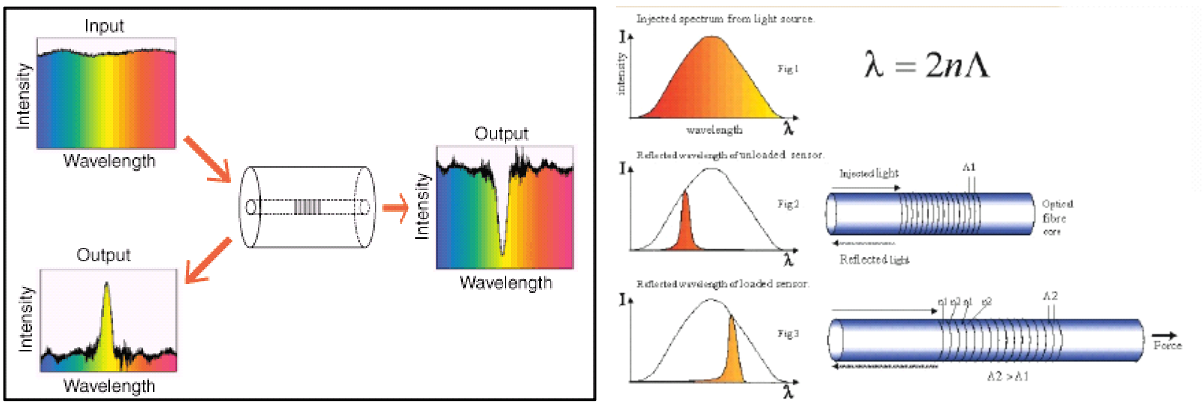

Figure 2. Principle of the Fiber Bragg Garting. (2a) : reflexion of a given wavelength (2a) and transmission of the remaining light spectrum. (2b) : the reflected wavelength is shifted as a linear function FBG strain.

2.2.2 The distributed scattering

On the contrary of FBGs, distributed scattering measures temperature and strain changes all along the optical fiber over several tenths of kilometers. A laser source sends inside the fiber a coherent light pulse of a given wavelength λ_0. At each point inside the optical fiber, the silica heterogeneities and the molecular vibrations create a back-refraction of the light with a spectrum shown in figure 3. A part of this light is back-refracted with the initial input wavelength λ_0 (Rayleigh peak). Secondary refracted light peaks are also visible on both sides of the wavelength λ_0, called Brillouin or Raman peaks. Variations of temperature and strain are changing the shape of these secondary peaks. The Brillouin peaks are shifting in wavelength when strain and/or temperature change. The amplitude of the Raman peak only depends on the temperature change.

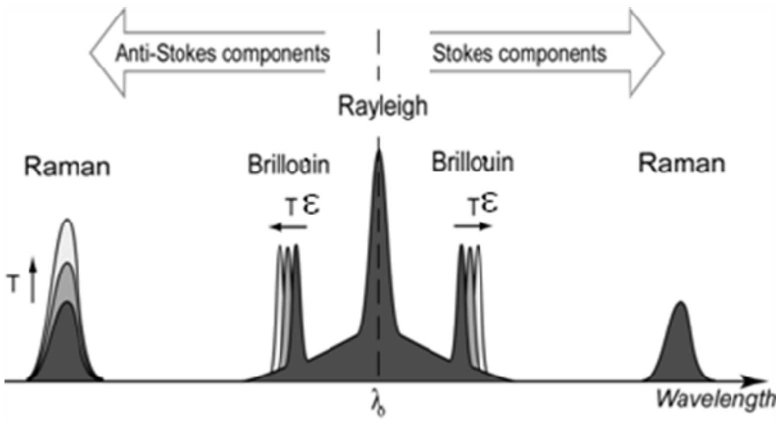

Figure 3. Back-scattered light spectrum (λ_0 is the input wavelength).

2.3. Performance and uses

Very small soil strain, from 0.02%, and temperature changes from 0.1°C can be detected with a spatial resolution of 1 m. This sensor has a small size (a few millimetres diameter) compared to larger conventional sensors that may disrupt the measured soil zone.

This solution can be used for long term surveillance, early warning of events or for a quick evaluation of an earthwork performance. Continuous and permanent monitoring can transmit remotely data for real time analysis. For each project, threshold values can be set up for the warning system. Depending to the project needs, it is possible to have control on the equipment either manually on site or remotely.

3 Feed back on the first earthworks installed in 2004

3.1. Bridge abutment reinforced with geotextiles

The first bridge abutment reinforced with geotextiles was built and monitored in July 2004 in the surrounding of Le Mans – Saint Saturnin (France). This earthwork is desbribed by Nancey et al. (2006). Three strips of the fiber optics geotextile enabled sensor have been installed in a vertical section of the abutment (Figure 4). The analysis of the strain measurements shows that the reinforced structure is under tension from the start of the construction and during the loading, but quickly stabilizes after construction. The last data report in 2010 shows a good behavior of the structure and very small variation of the service strain (Figure 5) which are globally smaller than 1%.

3.2. Monitoring and warning system under a railways embankment crossing an area with suspected underground cavities

After the detection of a crack perpendicular to the railways line between Mouchard and Bourg is the Arbois zone (France), the French railways company (SNCF) decided to reinforce the suspected area with a reinforcement and optical fibres warning system, on ones side to prevent any deleterious collapse and settlement at the level of the railways and on the other side to detect localised settlements to avoid any train to cross a cavity larger than 1.5 m. The covered area is 50 m long and 5 m wide for a single lane. The railways platform is built with 25 cm of ballast and 50 cm of soil.

The geotextile enabled sensor installed in this section combines both Fibre Bragg Gratings (FBG) written every 0.85 m along 5 optical fibres 0.85 m apart and reinforcement yarns to increase the tensile strength and modulus and to minimize the deflection at the embankment surface. There is network of 297 FBGs (Figure 6a) which can localise a 1.2 m diameter cavity with 2 different FBGs. A waterproof cabinet is installed close to the reinforced area (Figure 6b) to protect the reading and communication devices used to monitor continuously the area (Briançon et al., 2006).

Despites hard installation conditions (rainfall, narrow working area, nightly work), the sensor panel was installed within the planning.

The combination of the sensor system with the geotextile for reinforcement improves the ease of installation that could not be achieved with traditional local sensors.

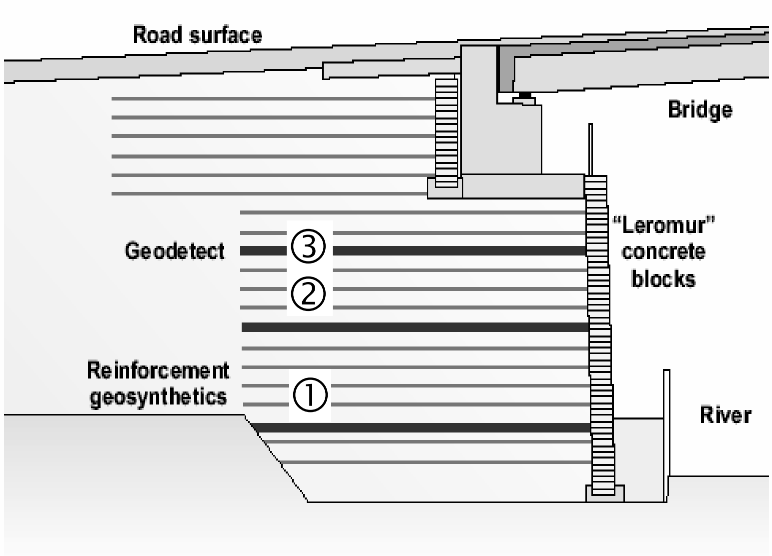

Figure 4. Cross section of the bridge abutment reinforced with geotextile in Saint-Saturnin and location of the 3 sensor strips.

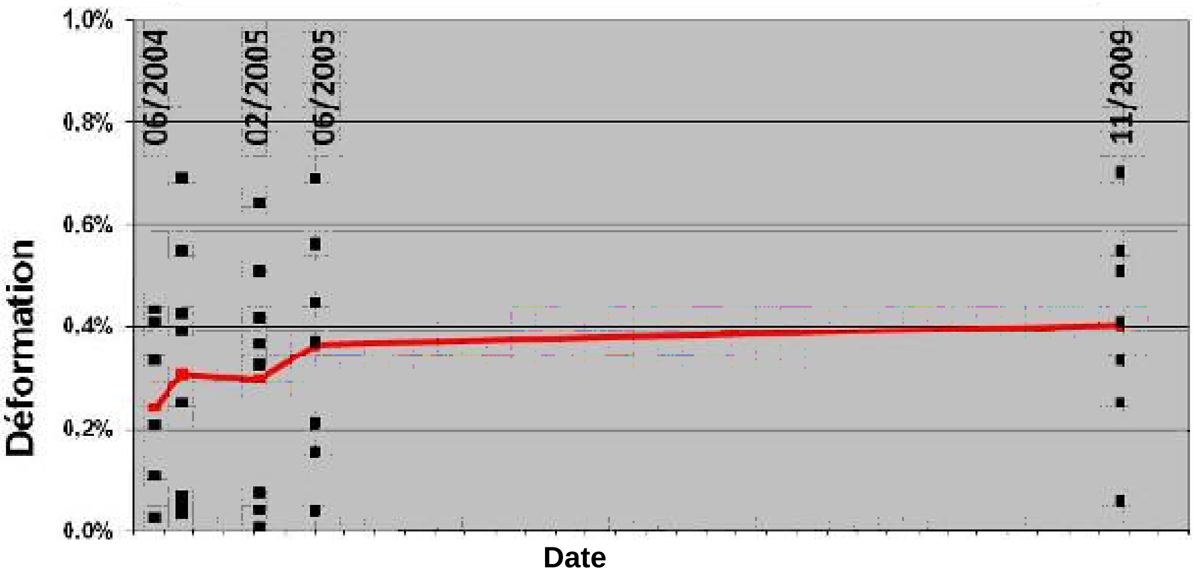

Figure 5. Evolution de la déformation moyenne de la bande n°2 entre 2004 et 2009.

The strain measured during the build-up of the embankment is smaller than 0.5%. The warning system is now installed for 7 years. The sensor measurements are stable since installation and don't change significantly. The threshold level fixed at 2% strain, corresponding to a deflection of 2 cm at the rail level is not reached yet (Figure 7). Also the connection of a dynamic interrogator allows acquiring high frequency data (1 kHz); it is possible to detect changes in strain of about 0.3% during a train passes (Figure 8).

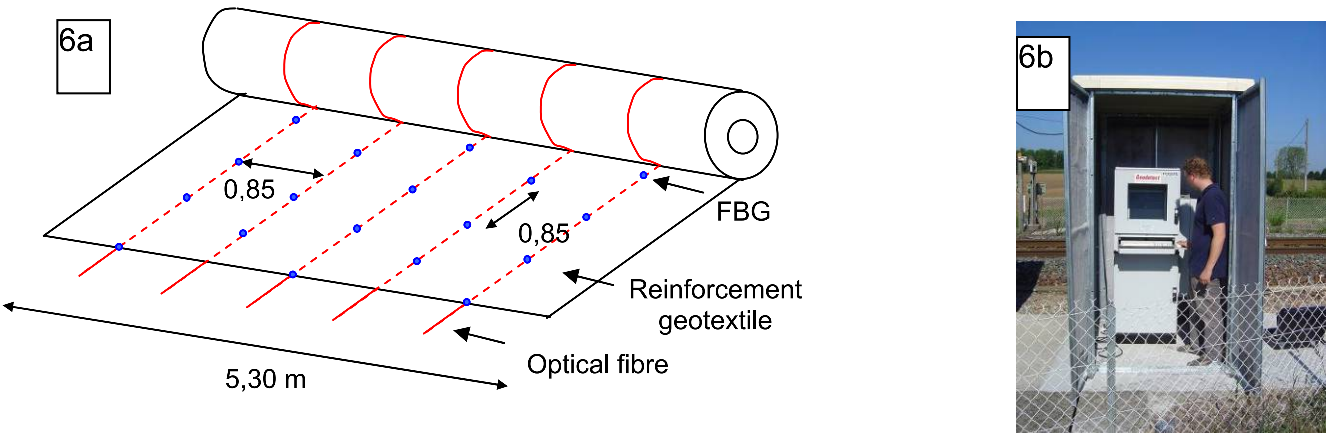

Figure 6. The fiber optics geotextile warning system installed bellow the railways line in the Arbois region. Distribution of the optical fibers and of the Fiber Bragg Gratings on the reinforcement geotextile (a) connected to the device for continuous measurement (b).

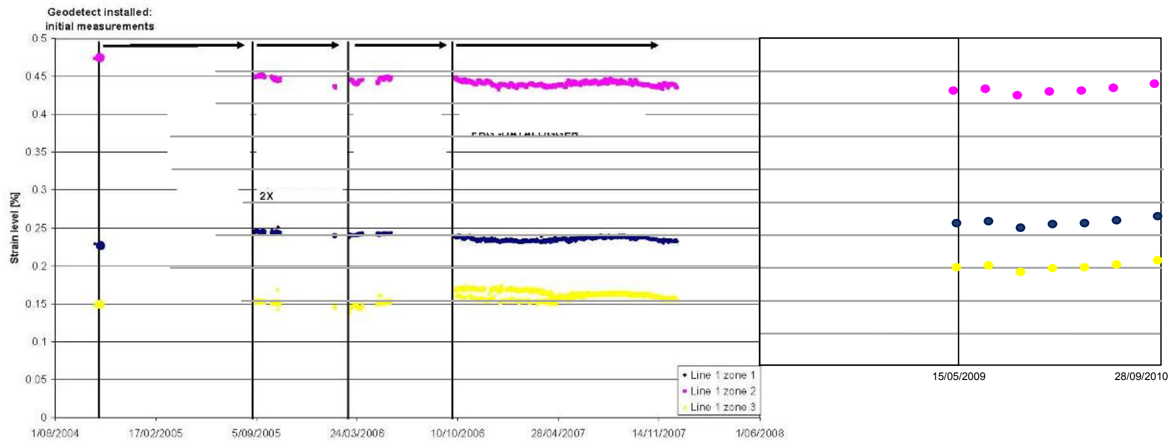

Figure 7. Strain changes measured on the line 1 under the railways embankment in Arbois between the installation in 2004 and September 2010.

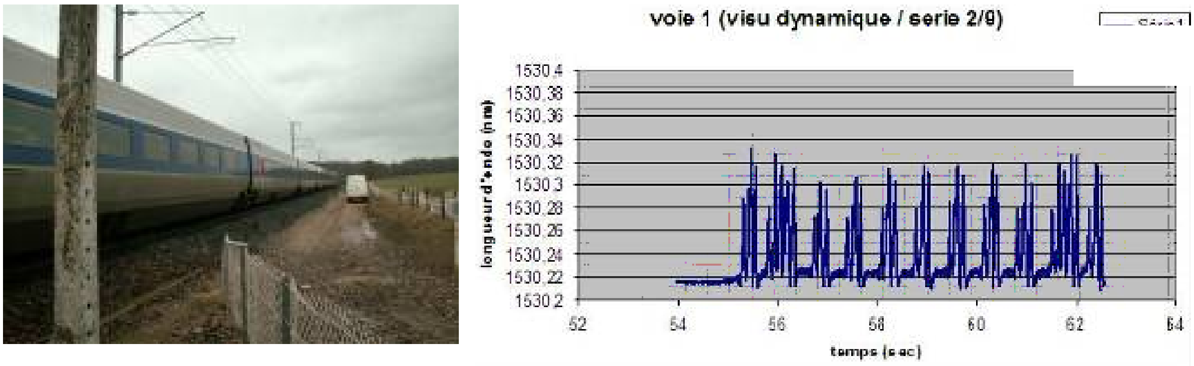

Figure 8. Railways in the Arbois area. Dynamic strain curve measured by the warning system during a train passes.

4 Monitoring and warning systems of dikes and levees

In hydraulic applications, this monitoring and warning solution aims to detect the two main causes of dike, earthdams or levees failures: structural instability (slippage, settlement) and internal erosion (leakage and increase of waterflow). This performance level has been assessed on three scale 1:1 experimental works.

The detection threshold of the leaks flowing through an homogeneous earthdike is very low: trials carried out on the dike of the PEERINE basin built in the testing facilities at the Cemagref in Aix-en-Provence described hereafter (high : 2,5 m, total length : 100 m) have shown a limit lower than 0,1 l/min/m (Artières et al., 2007).

Another series of 4 trials carried out in The Netherlands (IJkdijk-Piping, 2009) focussed on the detection of the early signs of internal erosion at the interface between a clayey dike and sandy erodible soils (Figure 9). They have shown that internal erosion channels can be detected as soon as the regressive erosion step starts, i.e. 5 days before the failure of the dike corresponding to only one day after the start of the test. This performance is due to the analysis of the thermal data with the models developed by EDF-DTG (Beck et al., 2010). It can also be observed that the strain measurement is complementary to thermometry for a better identification and localisation of the phenomenon (Figure 10).

Figure 9. Project IJkdijk/Piping – An experimental dike before and after failure

Another trial was carried out in the frame of the first Dutch IJkdijk/Macrostabilty project where a 100 m long and 6 m high monitored dike was stressed to the failure. The fibre optics geotextile enabled sensor was the first system able to detect the very small movement of the work (from 0.02%) and to notice this malfunctioning 2 days before failure, for a total testing time of 5 days (Artières et al., 2010b).

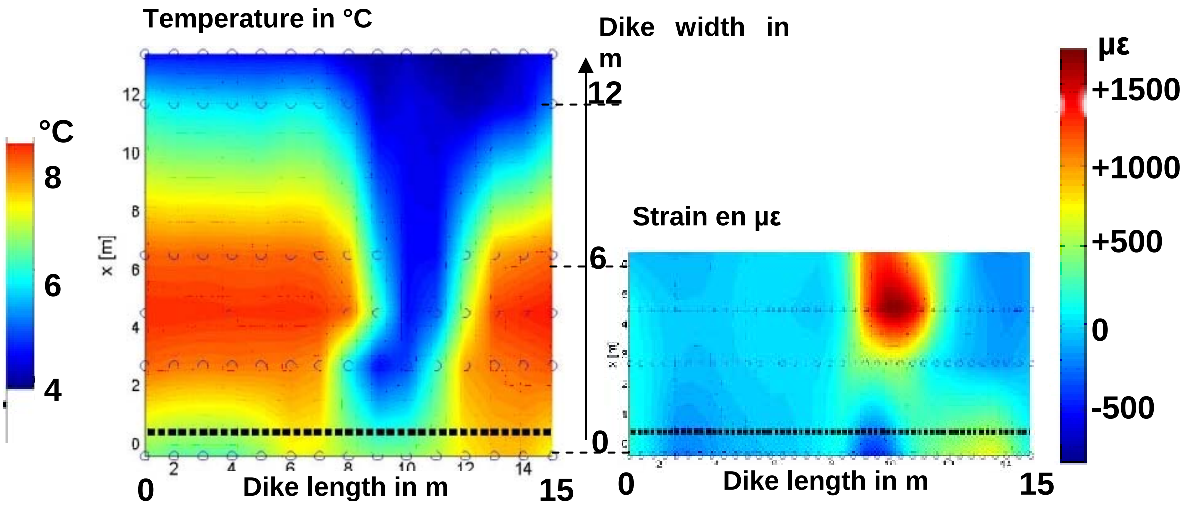

Figure 10. IJkdijk/Piping project - Detection of the piping channel below the dike (view from the top) by simultaneous measurement of temperature on the left and strain on the right. (Data processed by geophyConsult).

Figure 11. Installation of the fiber optics geotextile enabled sensor along the Marne to the Rhine canal dike (a) and on the flood protection levee along the Loire river / Authion (b).

Other applications in hydraulic constructions, such as on the wet dikes of the Marne to the Rhine canal or on the dry flood protection levee of the Loire river (France) (Figure 11) are described by Artières et al. (2010a). The combination of the high sensibility of this sensor with accurate data treatment tools makes a powerful early detection solution of dikes malfunctioning.

5 Monitoring of lining systems

5.1. Leak detection through thin lining systems

An experimental study was carried out on the PEERINE basin built in the Cemagref facilities in Aix-en-Provence (France) to assess the performance of the TenCate GeoDetect® system to detect leaks through a thin geomembrane lining system. The basin perimeter is 78 m on top and 118 m at the bottom (Figure 12). It has a storage volume of 200 m3. Openings through the liner controlled by constant waterflow dikes can simulate artificial leaks in different locations. The geomembrane lining structure is from the top to the bottom: (1) a top protection layer made with a needle-punched nonwoven geotextile covered with concrete slabs, (2) a 1 mm thick PVC geomembrane, (3) a protection and drainage layer with two options: either a 30 cm thick gravel layer between two geotextiles, or a geocomposite for drainage.

These two configurations are representative of the common lining structures of basins and canals. For each option, four geotextile enabled sensor strips are laid parallel to the crest between the drainage layer and the filtration geotextile, at different level from the toe to the top of the dike, including 2 strips in the middle of the slope (Figure 12), to detect leaks through the liner. The artificial leaks are localized between the top and the crest of the slope and can deliver waterflow from 0,2 l/min.

Figure 13 shows the temperature profile measured by the optical fibers which accurately localized the artificial leaks at the sensor strip at the toe level (blue curve) for all the leaks at the bottom (black arrows), at the middle (purple arrows) and at the top (red arrows) of the slope. The sensor strip at the middle of the slope (green curve) localizes the leaks from the middle and the top.

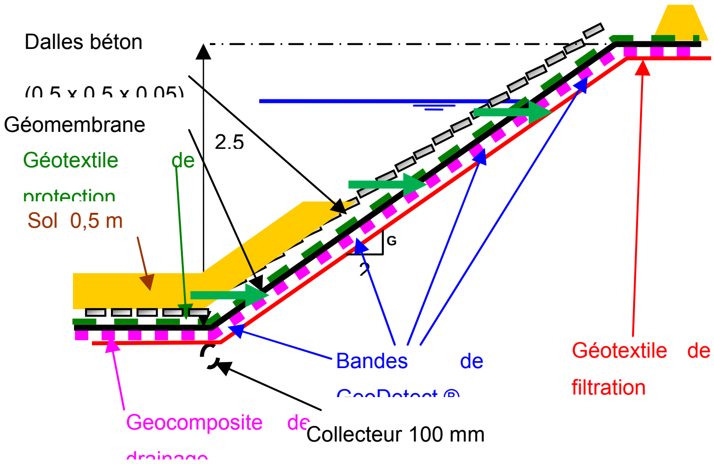

Figure 12. Experimental PEERINE basin at the Cemagref in Aix-en-Provence.

Cross-section of the slope with the drainage geocomposite. Green arrows : artificial leaks.

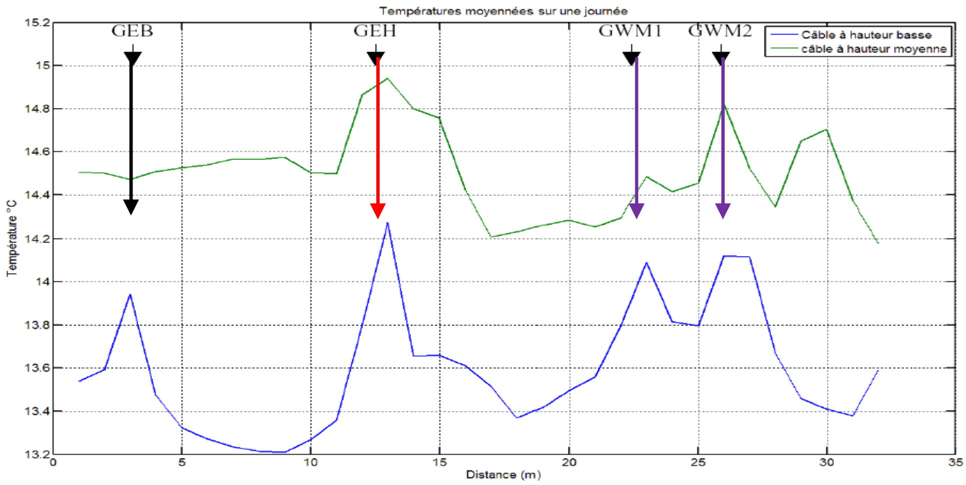

Figure 13. Detection of the artificial leaks (arrows) with the fiber optics geotextile enabled sensor for the sensor strip installed at the toe (blue curve) and at the middle (green curve) of the slope.

5.2. Mesure des déformations au-dessus d'une géomembrane de couverture d'ISD

The rehabilitation of the old Amsterdam landfill (The Netherlands) on the site of the Volgermeer polder required a capping liner with a 2 mm HDPE geomembrane. The landfill is over a compressible peat subsoil. On the top of the capping are built water ponds of 30 by 50 m for wild birds. The geomembrane surface is rough on the slopes and smooth in the bottom of the pond. It is covered with a sand layer of 50 cm. The ponds are progressively filled with rainwater during about 1 year.

The company Witteveen+Bos which manages this rehabilitation project started more than 5 years ago want to follow up the geomembrane strain inside one pond when it is filled with sand and water. A total length of about 450 m of geotextile enabled sensor was unrolled at the bottom and on the slopes of the pond at the interface between the geomembrane and the sand. This continuous strip is anchored at the top of the slope with the load of sand. The rough interface with the geomembrane on the slopes increases the anchoring of the strip. The sensor strain is assessed with a distributed Brillouin measurement with a spatial resolution of 1 m. The results on figure 15 show that the maximum measured strain is smaller than 1.5 to 2%.

Figure 14. Volgermeer polder (NL) – Aerial view on the left. On the right : the pond lined with a geomembrane and monitored with the TenCate GeoDetect® optical fiber geotextile enabled sensor.

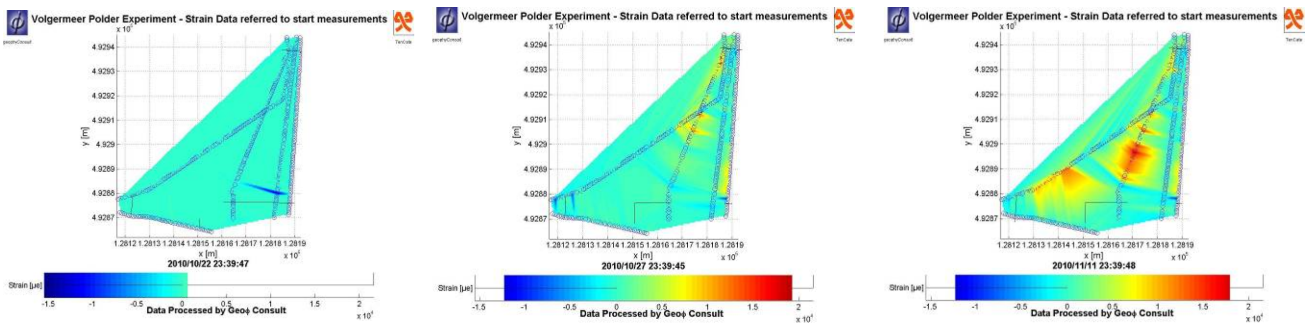

Figure 15. Strain measured on the top of the geomembrane capping liner in the Volgermeer polder on October 22nd and 27th, and November 11th from the left to the right. Colour scale in % (data processed by geophyConsult)

6 Conclusions

The monitoring and early warning solution described in this paper combines the functions of the geotextile products with the properties of the most recent measurement technologies with optical fibres, to offer important information (temperature and soil strain) to manage accurately earth- and hydraulic works, in particular those including geosynthetics, during construction and on the long term as well.

The feedback from structures monitored since 2004 with this solution show the reliability of this technology. The range of applications is very wide. Besides reinforced slopes and walls, reinforced platforms and embankments, the TenCate GeoDetect® solution is also very convenient to monitor and generate warnings on longer infrastructures such as roads, railways and dikes. In this case, the combined measurement of temperature and strain with the distributed method can detect the early signs of malfunctioning, such as leaks or settlements.

This solution helps to reduce risks and reduces the costs substantially. Developed to fit the specific requirements of each project, it offers owners and design engineers insight into the performance and sustainability of soil structures. This additional reliability and integrity can assure the appropriate performance of a geo-structure – leading to better land use, longer lasting structures, lower overall project costs, increased factors of performance, and broadened geosynthetic applications.

7 References

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