

Monitoring of Earthdams Leaks and Stability with Fibre-Optics based Monitoring System

O. Artières¹, Y.L. Beck², J.J. Fry³, C. Guidoux⁴ and P. Pinettes⁴

¹Tencate Geosynthetics, 9 rue Marcel Paul, BP 40080, F-95873 Bezons, France

²EDF-DTG, 21 avenue de l'Europe, BP41, 38000 Grenoble, France

³EDF-CIH, Savoie Technolac, 73373 Le Bourget du Lac Cedex, France

⁴geophyConsult, 12, allée du Lac de Garde, BP 231, 73374 Le Bourget-du-Lac, France

E-mail: o.artieres@tencate.com

Abstract

The GeoDetect[®] monitoring system is based on the combination of a technical textile with embedded fibre optic cables that are connected to optical instrumentations to measure the temperature and the strain of the soil. The strain resolution can be as little as 0.02% and the temperature resolution as little as 0.1°C, with spatial resolutions of 1 m at up to 20 km distance. Provided the implementation of the system within the work is designed properly, the analysis of the thermal data enables the detection of very small leaks, which are indicative signs of early stages of either internal erosion processes, or dike settlement by analysing the strain measurements. It has been tested in two different test series in the Dutch experimental IJkdijk project. In the first macro-instability test, the monitoring solution has been the only system able to detect and localize the start of the dike sliding more than 2 days before its collapse. In the second piping test series, it has been able to generate real-time alarms 2 days prior to failure. A post-failure analysis that is about to be included in real-time data analysis modules has revealed the presence of precursors 5 days before collapse.

Introduction

Monitoring the behavior of new and old dams is a key issue in the field of dam maintenance. Thanks to the early detection of precursors of malfunctioning such as leakage, erosion, relative deformation or settlement, it is possible to react very fast when necessary or to check periodically the slow dam ageing process and to plan the maintenance works in due time.

The TenCate GeoDetect[®] monitoring technology detects both internal erosion and instability at an early stage. It is based on the combination of a technical textile with embedded fiber optic cables that are connected to appropriate optical instrumentations to measure soil temperatures and strains. The current performance of the GeoDetect[®] global solution

has been validated in France and in The Netherlands: the strain resolution can be as little as 0.02% and the temperature resolution as little as 0.1°C, with spatial resolutions of 1 m up to 20 km in distance.

It has been used in two different test series in the recent Dutch experimental IJkdijk project. In the first test series, based on the simulation of a 100 m long macro-instability dyke, the GeoDetect[®] solution has been the only system among ten others able to detect and localize the start of the dike slide more than 2 days before its collapse during the 4 full days of experimentation time. In the second test series, based on the simulation of piping, it has been the only system able to generate real-time alarms, 2 days prior to failure. The GeoDetect[®] monitoring and early warning solution is now being used in several real sites.

After introducing the principle of this monitoring solution and describing its real performance based on the experimental dikes, the installation and the data analysis on several dykes will be described.

The fiber optics based monitoring solution

The textile fiber optics composite sensor

The fiber optics have been widely used for many years in civil engineering applications and specially hydraulic works such as concrete and earthdams, levees and dikes. By embedding optical cables into a geotextile fabric (Figure 1), GeoDetect[®] is the first system designed specifically for geotechnical and hydraulics applications. The geotextile fabric, e.g. a textile installed in the soil, enhances its mechanical and hydraulic properties by in-plane drainage capability, anchoring interface with the soil, soil reinforcement, separation and filtration. For example the drainage properties of the geotextile combined with the temperature measurement with the optical fibers improves the speed of leakage detection by collecting the water-flow and draining it faster to the optical fiber. Moreover, the filtration properties of the geotextile increase the stability of the soil to prevent the internal erosion process.

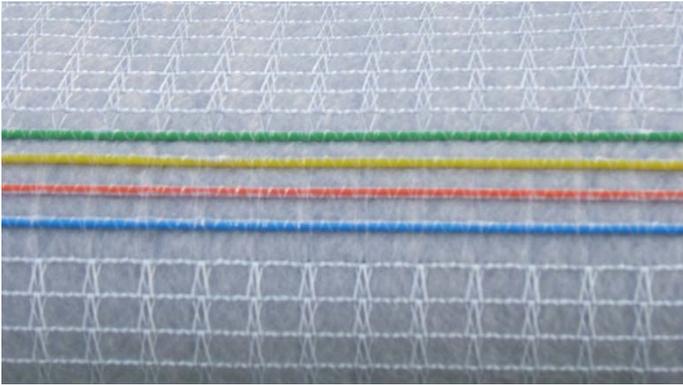


Figure 1: The TenCate GeoDetect® S-BR textile composite sensor embedding 2 optical cables for temperature and 2 for strain measurement



Figure 2: The Raman instrumentation for temperature measurement (on top) and the Brillouin instrumentation for strain measurement (at the bottom)

Also the high soil-textile interface friction properties and the strong link between the optical cable and the geotextile help to transfer and detect very small soil strains. The GeoDetect® sensor is designed to detect the first steps of internal erosion processes and hydraulic works instability. The detection of the leaks, which is the early stage of the internal erosion process, is assessed through the measurement of temperature changes using the passive method or the active heat pulse method [1]. First stages of dike settlement or sliding are detected by strain measurement. Measuring at the same time and at the same location both temperature for leaks detection and soil strain for soil movement detection increases the probability of obtaining the right precursors of a

malfunctioning.

This development was handled through a partnership of companies and public research institutes including several authors of this paper within the European Eureka R&D project “SafeDike”.

The monitoring and early warning system

The GeoDetect® monitoring system combines the benefits of geotextile materials with the latest optical sensing and measurement technologies. It uses either the stimulated Brillouin or Raman scattering technology in single mode or multi-mode optical fibers to measure both strain and temperature, or local Fiber Bragg Grating (FBG) sensors placed on single mode fibers to measure strain very precisely both under static or dynamic conditions.

Combined with the appropriate software and instrumentation (Figure 2), it provides an innovative solution for the multi-functional requirements of geo-technical and hydraulic applications in addition to data capture. Different monitoring strategies may be designed, for example temporary monitoring, or continuous monitoring to be used as an early warning system.



Figure 3: Installation of one GeoDetect® S-BR sensor strip in the IJkdijk macro-stability dike.

In comparison to existing detection systems, the GeoDetect® solution is a distributed and continuous measurement along the whole hydraulic works length, which increases the accuracy and the speed of response, both crucial parameters to prevent collapse. It can provide a leak and deformation location with a spatial resolution of 1 meter, or even 0.5 m in some cases. The system is able to monitor several tens of kilometers.

The full monitoring solution

Beside the hardware components of the system, important parts of this global solution are the design and implementation of the system within the work (Figure 3) and the interpretation of the raw thermal and strain data. The detection of very small water pipes (or wormholes) for example has been improved recently. The physico-statistical and signal processing methods developed by EDF and used by geophyConsult allow the proposed system to be able to send « early warnings » which is compatible with long-term monitoring. The GeoDetect® solution has been validated on several 1:1 scale experimental works and real dikes in-use, as presented in the next sections.

Performance evaluation of dam stability monitoring

First stages of dike settlement or sliding are detected by strain measurement. An experimental dyke 100 m long and 6 m high was built within the Dutch IJkdijk (Smart Calibration Dike) project to test the ability of sensing systems to detect dam failure due to internal instability (Figure 4). The IJkdijk-site is located in the North-East of the Netherlands, close to the German border.

Experiments were carried out with the following objectives. The first goal was to test whether the state-of-the-art multi-sensor networks and IT-tools can supplement standard visual inspections and existing water management systems. About ten different techniques were used. The second objective was to obtain knowledge about failure mechanisms and to carry out model validation [2]



Figure 5: Placement of the 4 GeoDetect® sensor strips along the IJkdijk macro-stability dike, at the crest (TOP), at the middle of the slope (MIDDLE), at the dike downstream toe (TOE), and 2 m from the downstream dike toe (FIELD).

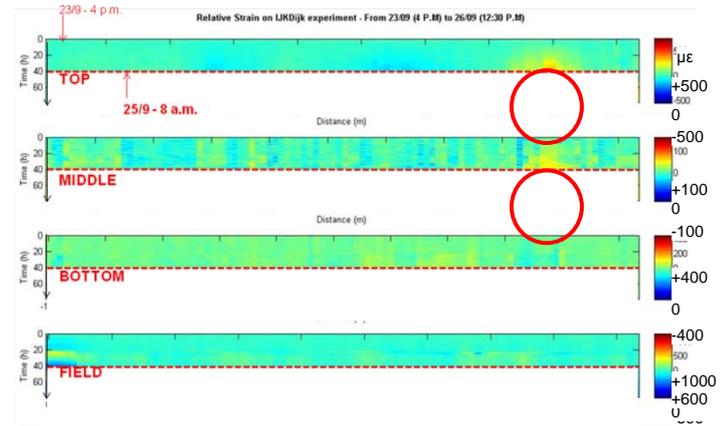


Figure 6: Relative strain measured on Sept. 25th 08:00 a.m. with the TenCate GeoDetect® system, 2.5 days before dike collapse : 0.03 % on the top strip, 0.005% on the middle strip (geophyConsult data processing).



Figure 4: Aerial view of the IJkdijk experimental dike during the macro-stability experiment, the upstream basin on the left filled with water, loading containers on top, and the trench digged out 2 m from the dike toe.

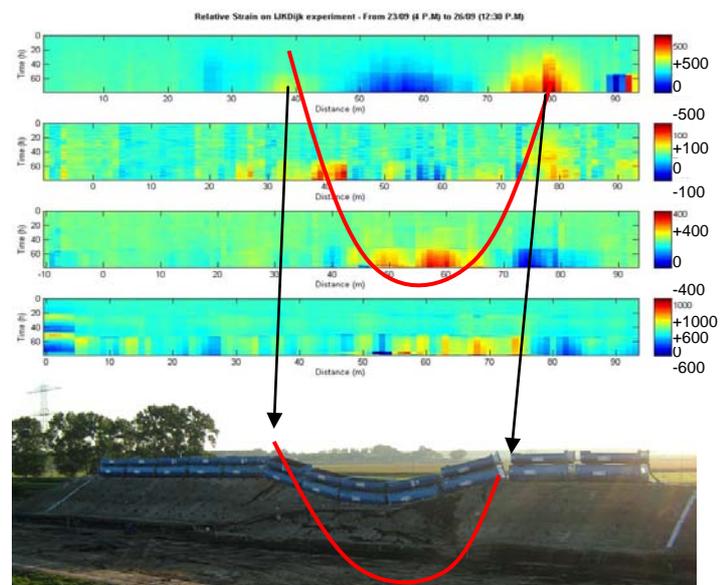


Figure 7: Relative strain measured on Sept. 26th 04:00 p.m. with the TenCate GeoDetect® system, 1 day before dike collapse : the tension zones on each strips draw the boarder of the slope slipping area (geophyConsult data processing).

The fiber optics GeoDetect® system was installed lengthwise to the dike at four different levels: top on the crest, at the middle, at the toe of the down-stream slope, and 2 m meters away from the downstream toe (Figure 5). The four strips, 100 m long each, were all connected together in a loop to the instrumentation in a cabinet at about 50 m from the experimental dike. Both optical cables for strain measurement using the Stimulated Brillouin Scattering and for temperature compensation measurement using the Raman Scattering technologies were embedded onto the textile strips.

In September 2008, during the test, the global factor of safety of the dyke was decreased step by step by digging a trench at the downstream toe and by increasing the internal water pressure till failure by slippage of an area of the downstream face. The failure took place on the third day of the test, during bright sunny conditions. The visible part of the failure took only 40 to 50 seconds, so it was a fast process. The monitoring system worked perfectly as it was able to detect and localize the early signs of soil movements 2.5 days before the dike collapses, i.e. only one day after the start of the experimentation. Very small soil strains of 0.03 % on the top strip and less than 0.01% on the middle strip were measured, see round red circles in Figure 6. The borders of the instable zone inside the dyke body were clearly localized more than one day before the failure occurred, when nothing was visible from out-side (Figure 7). They exactly correspond to the area of the slipping slope.

Soil strain detection and measurement with the GeoDetect® monitoring solution had already been proven in previous earthworks, such as walls or embankments over instable soils, with another fiber op-tics technology, the Fiber Bragg Gratings (FBG) [3] [4]. This IJkdijk macrostability experimentation, confirmed the capability of this system to detect and localize small soil strains in hydraulics works on longer distances by using the Brillouin distributed scattering technology.

Performance evaluation of dam internal erosion detection

Another series of 4 experimentations was carried out in 2009 during the second IJkdijk-Piping experimental project for the detection of the early signs of internal erosion at the interface between a clayey dike and sandy erosive subsoil. Full scale levees were built and brought to failure with two explicit goals: to increase the knowledge on levee behavior and to develop and test new sensor technologies for early warning systems under field conditions [5]. Four experiments have been carried out, aiming at failure caused by under-seepage erosion (piping). The clay levee with a height of 3.5m and slopes of 1:2 was built on top of the sand, 15 m long and 12 m wide. To create erosive channels, water head was increased step by step up to 3 m maximum, to obtain sufficient hydraulic forces to generate an internal piping process. The downstream toe of the dike was inspected visually and

continuously to detect water outlets, with or without soil transport. The test stops when the dike collapses (Figure 8).



Figure 8: Downstream side of the IJkdijk experimental dyke a few minutes before collapse with clear view of the piping channel and sand erosion at the toe. The coloured labels at the toe indicate the observed flows, red with sand transport, blue only water (from Stichting IJkdijk).



Figure 9: Location of the 6 GeoDetect® strips into the sand below the IJkdijk experimental dike.



Figure 10. Installation of the GeoDetect® sensor strips embedding both strain and temperature fiber optics 10 cm into the sand layer before construction of the dike.

As for the macro-stability project, several detection methods were tested. Among them, the GeoDetect® system was installed in the test number 4 : three textile sensor strips embedding fiber optics for both temperature and strain measurement were buried 10 cm into the sandy subsoil lengthwise the dike at three different locations ITA0, ITA1 and ITA2 from the downstream toe of the dike as indicated in figure 9. The temperature optical line was connected to Raman Scattering instrumentation, the strain optical line was connected to Stimulated Brillouin Scattering instrumentation. Even though the right detection place would be the interface

between the sand subsoil and the clayey dike, as it is where the higher hydraulic gradient occurs, the strips were only allowed to be buried into the sand so as not to disturb the erosion process to be studied during this experimentation. Three other strips with only temperature optical fibers were installed further up on the upstream toe of the dike at the positions ITA3, ITA4 and ITA5.

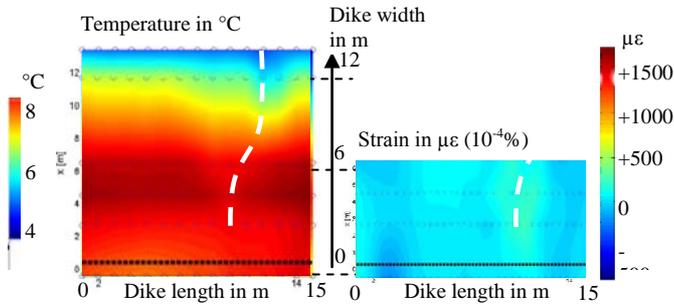


Figure 11: IJkdijk piping dike - Temperature (left) and strain (right) profiles measured on Dec. 4th 06:00 p.m. with the TenCate GeoDetect® system, 22 hours before dike collapse. Heterogeneities appear on the map (white dot line) (geophyConsult data processing).

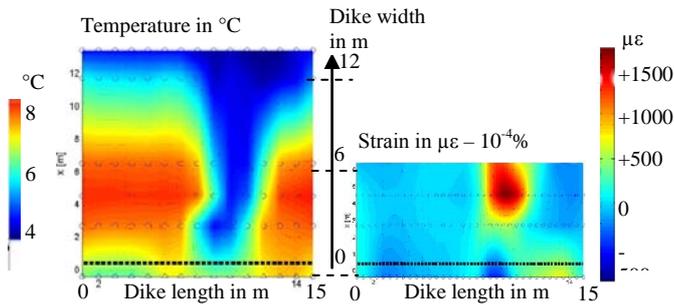


Figure 12: IJkdijk piping dike -Temperature (left) and strain (right) profiles measured on Dec. 5th 11:00 a.m., 5 hours before dike collapse from the raw data on the Ijkdijk piping test n°4 showing the extension of the piping channel bellow the dike (geophyConsult data processing).

Figure 11 shows the maps of the raw temperatures (left column) and of the relative strains (right column) measured by the GeoDetect® system. The temperature profile is disturbed due to the penetration of a colder water flow inside the dike body at distance of about 12 m from the left upstream corner and an inflection of the channel inside the dike body predicting a channel outlet in an area between 8 to 10 m from the left downstream corner. The strain profile on the left is also slightly modified at the same distances with an elongation of the sensors corresponding to about 500 $\mu\epsilon$ or 0.05 % (dotted white lines). From the observation of these two parameters, this clearly indicates that the start of the piping channel from the upstream side to the down-stream side of the dike took place before December 4th, 2009 at 6

p.m., i.e. more than 15 hours before the dike failure occurs. This is confirmed by the evolution of these parameters till December 5th, 2009 at 11 a.m (Figure 12), 5 hours before the dikes collapses (Figure 13).



Figure 13: Collapse of the IJkdijk-Piping experimental dyke after the internal erosion process is completed (from Sticing IJkdijk).

A post-failure analysis carried out by EDF on a another experimental dike (IJkdijk Piping test n°2) based on signal processing models developed by EDF that is about to be included in real-time data analysis modules has revealed the presence of precursors 5 days before collapse, i.e. only one day after the start of the experimentation [6]. It has also been observed from the temperature measurements that the speed of the detection increases when the optical cables are located where the leaks are fore-seen, here at the interface between the sand and the clayey dike, which would be the case for a non experimental work.

This IJkdijk-piping experimentation clearly demonstrates the capabilities of the GeoDetect® system to detect the early stage of a piping process, by analyzing together temperature measurement corresponding to very small leakage rates, less than 1 l/min./m as previously observed in other sites [7], and very small soil strain movements less than 0.1%.

Conclusion

Monitoring old and new dams has become a very important issue for their maintenance and the safety. Solutions based on the fiber optic technology demonstrated over the past 5 years have proven their performance in detecting the early signs of dam ageing. Among them, the GeoDetect® monitoring system, with the embedment of several optical fibers for both temperature and strain measurement is very sensitive to detect small temperature changes as little as 0.1°C, small leaks from 0.1 l/min/m and light soil strain as little as 0.02 %. Combined with the proper design, installation and a deep raw data analysis from robust signal processing models it is shown to be a powerful early warning solution. It provides

dam owners with unique information that drives risk reduction and optimizes the cost of their maintenance strategy.

References

- [1] Radzicki K., Bonelli S., Beck Y.L. & Cunat P. (2009). *Leakage and erosion processes identification by temperature measurements, in upstream part of earth hydraulic works using the impulse response function analysis method*. European Working Group in Internal Erosion, St Petersburg, Russia.
- [2] Ijkdiik (2008). *Ijkdiik macrostability-experiment*. Sticking Ijkdiik, available on www.ijkdiik.eu, 4 p.
- [3] Briançon L., Nancey A., Robinet A. & Voet M. (2006). *Set up of a warning system integrated inside a reinforced geotextile for the survey of railway*. Proc. 8th Int. Conf. on Geosynthetics, Yokohama, Japan. Geosynthetics, J. Kuwano & J. Koseki (eds), Balkema, Rotterdam: 857-860
- [4] Nancey A., Rossi D., Boons B. (2006). *Survey of a bridge abutment reinforced by geosynthetics, with optic sensors integrated in geotextile*. Proc. 8th Int. Conf. on Geosynthetics, Yokohama, Japan. J. Kuwano & J. Koseki (eds), Balkema, Rotterdam: 1071-1074
- [5] Ijkdiik-Piping (2009). Leaflet available on the website www.ijkdiik.eu. 4 P.
- [6] Beck Y.-L., Khan A. A., Cunat P., Guidoux C., Artières O., Mars J., Fry J.-J. (2010). *Thermal monitoring of embankment dams by fiber optics*. Proc. 8th ICOLD European Club Symposium on dam safety, Innsbruck, Austria; September 22-23, 2010.
- [7] Artières O., Bonelli S., Fabre J.-P., Guidoux C., Radzicki C., Royet P., Vedrenne C. (2007). *Active and passive defenses against internal erosion*. Proc. 7th ICOLD European Club Dam Symposium. Freising (Munich), Germany, September 17-19, 2007. 10 p.