DEPLOYMENT OF A FIBRE OPTIC LEAKS AND SEEPAGES DETECTION SYSTEM BELOW A WATERPROOFING GEOMEMBRANE ON UPPER BHAVANI DAM

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ABSTRACT

Although geomembranes represent a very safe solution for old dams waterproofing, they may remain sensitive to damages from mechanical impacts of any type. In order to reduce this vulnerability, development of low-cost technologies that enable operators to immediately detect and locate leaks as soon as they appear are requested. A competitive technology available to achieve this goal is fibre optics distributed temperature monitoring that enable to infer the presence of leakages from the temperature variations all along a fiber optic path with a very high resolution (up to 0.2 m). This type of measurement is acknowledged as particularly adapted to applications that require dense arrays of measurements or extended monitoring zones, such as dam faces or water reservoir faces.

The ability of fibre optics to actually detect and locate leaks below geomembranes has been experimentally demonstrated in 2018 using heated fibre optics cables. The results gathered from this experiment were used to design an industrial leakage detection system dedicated to the surveillance of the geomembrane. This system is currently being installed on the Upper Bhavani Dam, in India. The present paper deals with the design and the on-going deployment of this system.

1. INTRODUCTION

1.1 Waterproofing using geomembranes

Waterproofing old dams is often a very interesting alternative to reinforcing or repairing them, as it significantly lengthens their lifespan for rather limited an investment, in particular when compared to the cost of structural reinforcements. In the same perspective, watertight membranes are obviously a key element for the performance of water reservoirs that are located on non-watertight soils.

It is therefore of utmost economic interest to improve the effectiveness of today waterproofing techniques.

Although geomembranes (GM) and geocomposites represent a very safe solution (strict quality control during the production in factory, high resistance, high deformability able to adapt to various movements such as settlements or seismic displacements), they may remain, when uncovered, sensitive to damages from mechanical impacts of any type. The possibility that water can by-pass the area lined with GM cannot besides be totally ruled out.

In order to reduce this vulnerability, development of low-cost technologies that enable operators to immediately detect and locate leaks as soon as they appear are requested, as they would enable to immediately repair when necessary.

1.2 Fibre optic-based surveillance system

Although fibre optics are generally known only as excellent telecom cables, they can be used as competitive thermal or strain sensors : when properly instrumented at one of their extremities, they enable to measure the temperature or the strain all along their path with very high a precision (0.1°C in temperature, and up to a few microstrains in strain) and very high a resolution (up to 0.1 m, depending on the implemented optical technology) – go for instance at http://geophyconsult.com/faq/faq.html for an introduction to Fibre Optics Monitoring (FOM) and to the physical processes behind, as well as to the way this technique is used to monitor infrastructures.

This type of measurement is acknowledged as particularly adapted to applications that require dense arrays of measurements or extended monitoring zones, such as dam faces or water reservoir faces.

It is likely to be used to detect leaks on dams or water reservoirs that are waterproofed with GMs that are positioned on their upstream face. The principle of measurement is rather simple, provided that we assume that (1) a drainage geonet is installed on top of the surface to waterproof, (2) a fibre optics cable is pulled over the drainage geonet, over several back and forth horizontal lines covering the surface to monitor (see picture 1); and (3) the fibre optics cables include electric wires in which an electric currents are regularly forced to flow, so as to generate successive heat pulses all along the fibre optics cables. In case of seepage or leak, water coming out from the seepage or leak is then drained downwards within the drainage geonet until it intersects the nearest horizontal fibre optics line, where it speeds up the cooling of the heat pulse. The amplitude of the momentary generated heat pulse is thus reduced at all locations which are intersected by seepage or leak flows, with respect to all other locations (see figure 1). The detection of such anomalies with thermal measurements carried out all along the fibre optics cable that intersects the leak flows is known as the « Heat Pulse Method » (Perzlmaier et al., 2006 or Read et al., 2014).

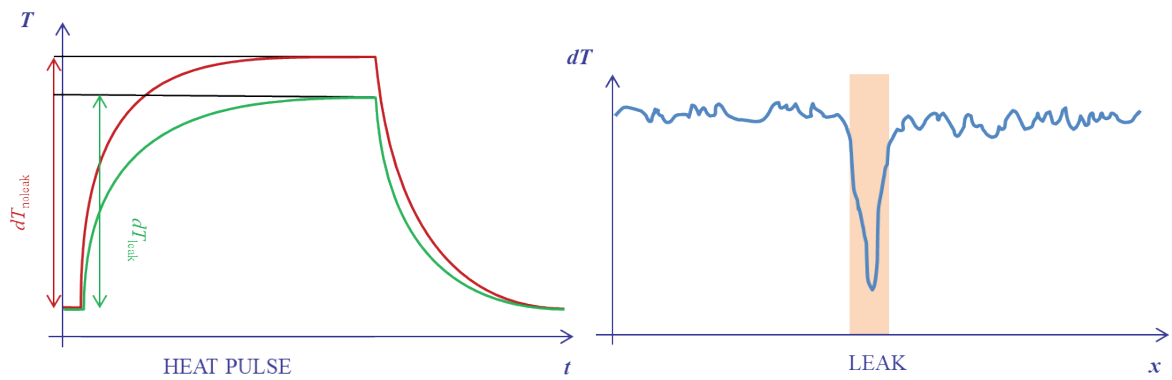

Figure 1 : Principle of detection according to the Heat Pulse Method (Perzlmaier et al., 2006). Left: generated heat pulse, with a low amplitude where it is intersected by leak flows (green situation) and a high amplitude elsewhere (red situation). Right: difference of temperature measured all along the fibre optics horizontal line just before and at the of the generation of the heat pulse, with the thermal signature of a leak at the middle of the line.

2 EXPERIMENTAL DEMONSTRATION

2.1 Experimental setup

The ability of fibre optics to actually detect and locate leaks below was experimentally demonstrated in 2018 (Guidoux, 2019), using a 1:1 dyke of about 22 m length, 3 m height, which closes a 14 m wide concrete reservoir (see Figure 2).

A drainage geonet has been installed on top of the upstream face of the dyke and a fibre optics cable has been pulled through the drainage geonet over two back and forth horizontal lines, so as to properly cover the face of the structure to monitor (see figure 3 and figure 4). The deepest horizontal line is called "Bottom" line, it is located about 85 cm above the bottom of the reservoir (ground zero or G0). The other one is called "Top" line, it is located about 110 cm above G0.

Figure 2 : EDF experimental setup in action (© EDF).

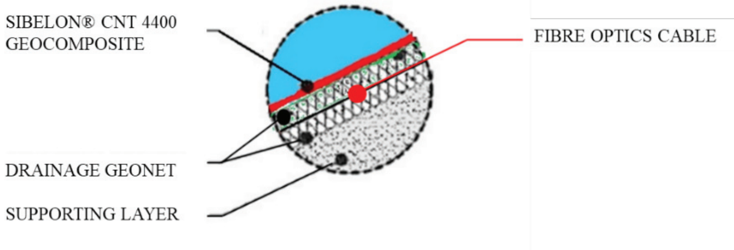

Figure 3 : Cross section of the position of the fibre optics cable within the sandwich composed of the GM and the upstream face of the structure.

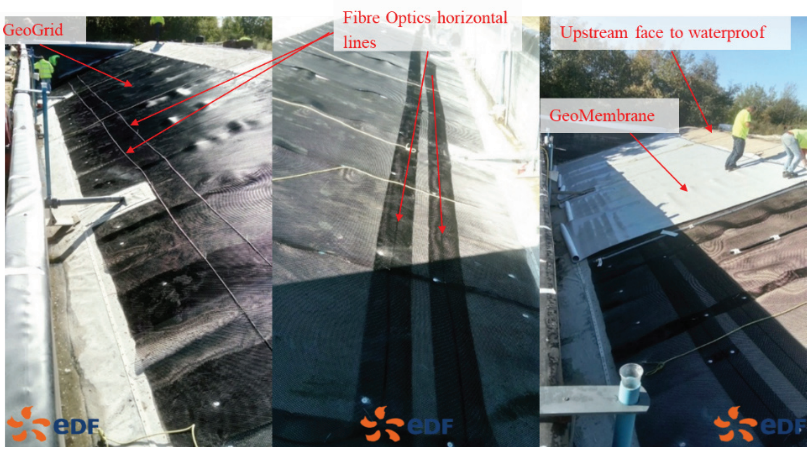

Figure 4 : Cross section of the position of the fibre optics cable within the sandwich composed of the GM and the upstream face of the structure.

On top of the drainage geonet, a standard CARPI geocomposite type SIBELON® 4400, consisting of a 3.0 mm thick plasticised Polyvinychloride (PVC) geomembrane heat-bonded during fabrication to a 500 g×m^2 non-woven, needle punched polypropylene geotextile, has been installed according to CARPI standard installation procedures.

In order to simulate seepages, at abscissa 12 m from the right rim of the dyke, a pipe has been inserted into the drainage geonet down to about 25 cm above the "Top" line, so as to enable water injections at a controlled rate in the drainage geonet, below the GM. And in order to simulate leaks, at abscissa 8.2 m from the right rim of the dyke, a 10 cm long vertical cut has been made through the GM about 25 cm above the "Top" line. The puncture has been covered by a removable plastic strip, so that the activity of the leak can be controlled (Guidoux, 2019).

In addition to those elements, 3 pipes have been installed at the bottom of the drainage geonet and linked to pumps working at a bigger pumping rate than the rate of the water which is injected (either via the pipe or via the puncture). The aim of these additional pumps was to ensure that the bottom of the drainage geonet remained properly drained during the test so that the space between the upstream face of the structure and the GM never got drowned.

The reservoir level and the pressure of the water at the bottom of the drainage geonet below the GM were permanently monitored with standard pressure gages.

The heat pulses were generated by a tailor-made electric device enabling to inject a few Amperes over 100 to 270 V in 4 or 6 electric wires of 0.5 mm^2 section, depending on the targeted elevation of temperature. The generated thermal anomaly ranged between 20 and 30°C, for an injected power ranging from 6 to 9 W×m^{-1}. The total length of the electric and optical circuits were equal to 114.2 m.

The optical fibres were standard Multi Mode fibres of 50 µm diameter. They were measured with a classical Raman interrogator which enabled to measure the temperature every 5 min with a spatial resolution 12.5 cm and a relative precision in temperature of the order of 10^{-1}°C.

During the installation phase, a detailed table of correspondence between the marks printed on the fibre optics cable and their actual location on site was established, so that the optical lengths delivered by the opto-electronics interrogator could be converted into precise locations on the experimental setup.

2.2 Detection results

Successive seepages of 10 l×m^{-1}, 5 l×m^{-1}, 1 l×m^{-1} and finally 0.5 l×m^{-1} have been tested. The results are given figure 5 for the "Top" line. Clearly, all the seepages above 1 l×m^{-1} have been detected and located, while the seepage of 0.5 l×m^{-1} has been of the order of the detection threshold.

In the same respect, one can note that the horizontal extension of the detection parameter anomalies were bigger on the "Bottom" line than on the "Top" line. Again, this was normal, as the water flow associated with the seepages naturally spread as it went further down from where it had been initiated.

The ability of the system to detect the leak generated by the puncture made in the GM at x = 8.2 m has also been tested, with various values of injected current (P_{inj} = 6 W×m^{-1} and P_{inj} = 9 W×m^{-1}) and of various water levels in the reservoir (1.5 m above G0 and 2 m above G0). Figure 6 clearly show that the leak has been detected and located in all the tested configurations, on both lines.

The water flow associated with the leak has not been measured precisely, as it has turned out not to be able to prime the pump dedicated to the draining of the drainage geonet . However indirect estimates of this water flow lead to a water flow of the order of 0.5 l×m^{-1}.

Assuming a security margin of 100%, we can thus assert that the system turned out to detect and locate seepages and leaks that were as low as 1 l×m^{-1}.

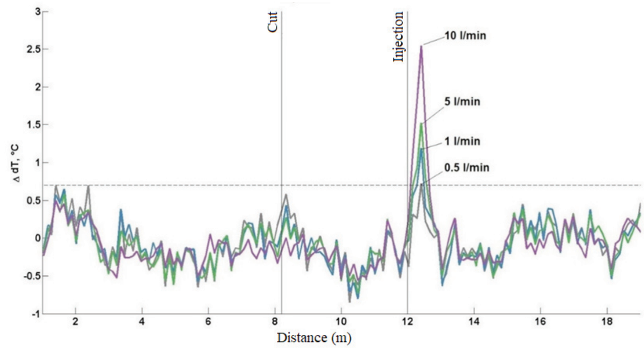

Figure 5 : Detection parameter during the seepage tests for the Top line. In purple seepage of 10 l×m^{-1}, in light green seepage of 5 l×m^{-1}, in dark green seepage 1 l×m^{-1} and in brown/grey seepage of 0.5 l×m^{-1}. The first vertical line represents the abscissa at which the puncture simulating the leaks is located, while the second vertical line represents the abscissa at which the water injected below the geomembrane to simulate the seepages is located. The horizontal line represents the threshold above which anomalies can be considered as potential leaks or seepages.

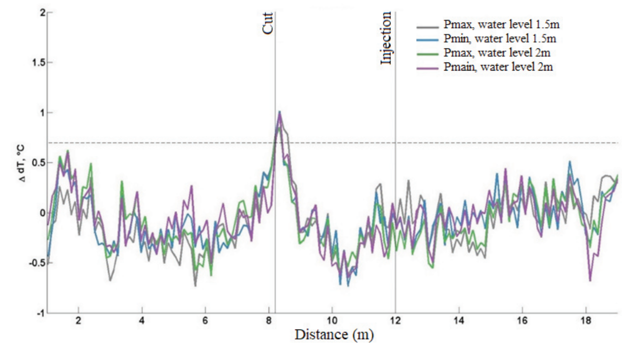

Figure 6.: Detection parameter on the Top line during the leak tests for various values of injected current and various water levels in the reservoir. In grey/brown current P_{inj} = 9 W×m^{-1} and reservoir level = 1.5 m above G0 ; in blue P_{inj} = 6 W×m^{-1} and reservoir level = 1.5 m above G0 ; in green Pinj = 9 W×m^{-1} and reservoir level = 2 m above G0 and in purple P_{inj} = 6 W×m^{-1} and reservoir level = 2 m above G0 . The first vertical line represents the abscissa at which the puncture simulating the leaks is located, while the second vertical line represents the abscissa at which the water injected below the geomembrane to simulate the seepages is located. The horizontal line represents the threshold above which anomalies can be considered as potential leaks or seepages.

2.3 Intensity of detection vs flow rate

In order to deduce the water flow associated with the seepage or leak generated below the geomembrane, geophyConsult and EDF have imagined a new parameter, called the intensity of detection level, that could be directly calculated from the detection parameter defined above each time a detection occured. Figure 7 shows that this parameter – as expected – is drastically influenced if not directly proportional to the water flow associated with the seepage or leak.

The geophyConsult and EDF intensity of detection parameter is therefore a very good candidate for estimating the water flows associated with the detected seepages or leaks.

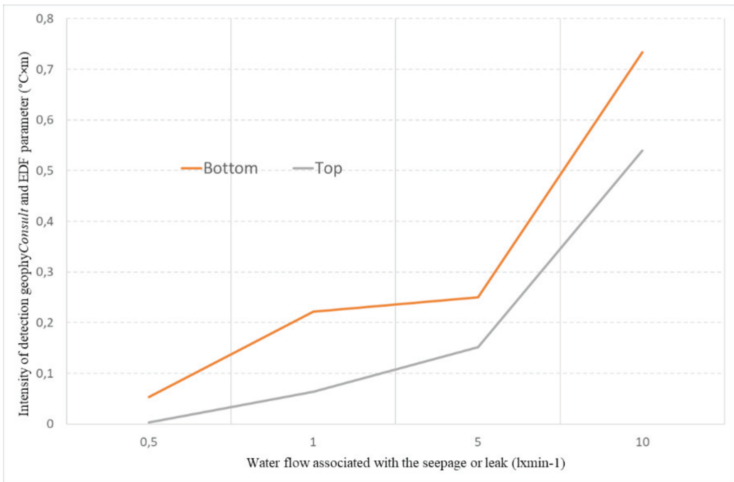

Figure 7 : Representation of the parameter called "Intensity of detection", as defined by geophy Consult and EDF, and calculated for the detections on "Top" (grey) and "Bottom" (orange) cables as a function of the water flow associated with the seepages or leaks that generated the detections.

3. INSTALLATION ON THE UPPER BHAVANI DAM

The carried out tests showed that seepages or leaks as low as 1 l×min^{-1} can be detected and located with a precision of the order of a few tens of centimeters with horizontal fibre optics cables properly installed on the upstream face of a hydraulic structures water proofed by a GM, provided the space between the GM and the structure face is properly drained at its bottom and provided the fibre cables are properly instrumented. Associated with a system that automatically detects all flows that are bigger than a given threshold (to be fixed by the structure owner), they thus can be used as a powerful and economic tool to instantly detect and locate leaks below GM. Associated with the calculation of the geophyConsult and EDF intensity of detection parameter, they can also estimate the water flow associated with the detected seepage or leak. The detection sensitivity of 1 l×min^{-1} turns out to be sufficient for industrial applications. In fact, it corresponds to the targeted performance of GMs on actual dams, dykes or water reservoirs.

Heating up to 10 W×m^{-1} hundreds of meters of electric cables is easily feasible with standard power generators. The investment costs of such a system are besides very low compared to the total cost of a waterproofing operation of a dam, dyke or water reservoir. The proposed solution is thus a priori relevant for waterproofing operations of dams or water reservoirs of width of the order of a few hundreds of meters and of height of the order of 50 to 100 m.

The deployment of the proposed solution has been initiated on several dams around the world, starting with the Upper Bhavani dam, in India.

3.1 The upper Bhavani dam

The Upper Bhavani Dam is a masonry dam located in the Nilgiris District (Tamil Nadu State, India), on which an upstream face lining with a Carpi Sibelon geomembrane is foreseen on the entire upstream face.

The dam was considered a distressed dam in 2005 and several repair attempts were made but none could provide a long lasting permanent solution and the client decided to go in for installation of Geomembrane waterproofing system on the upstream face similar to the one in their own Kadamparai dam installed in 2004-05 where the leakage was brought down from nearly 35,000 l×min^{-1} to nearly 100 l×min^{-1} and is still in service. The leakage currently was recorded in Upper Bhavani at 8000 l×min^{-1} at 8 meter below the Full reservoir level. Being a large dam with exposed area of around 20,000 sqm, the client expressed interest to have a surveillance system to monitor the efficiency of the geomembrane system and hence the decision to go in for optical fiber based measuring system.

Figure 8 : Overview of the dam with nearly 20% of the upstream face installed with Geomembrane system & Optical Fiber Cable.

3.2 Design

The main objective of the surveillance system is to detect and localize defects below the geomembrane, on the entire length of the dam. In order to do so, the leakage detection system has been designed with:

- 4 fibre optic cable loops located under the GM. The lowest measurement lines are located above the drainage gallery;
- 8 waterproof optical connection boxes under the GM (red boxes on figure 9). These boxes are mandatory because the works has been planned on two or three years, therefore the cables have to be cut into pieces before the installation on each work area, then they have to be spliced in order to restore the optical continuity of each measurement line;
- 4 or more optical connection boxes and one heat command rack at the crest of the dam, housed in 4 concrete shelters (blue boxes on figure 9);
- 1 measurement device;
- 1 power supply for the measurement device and the heat command rack.

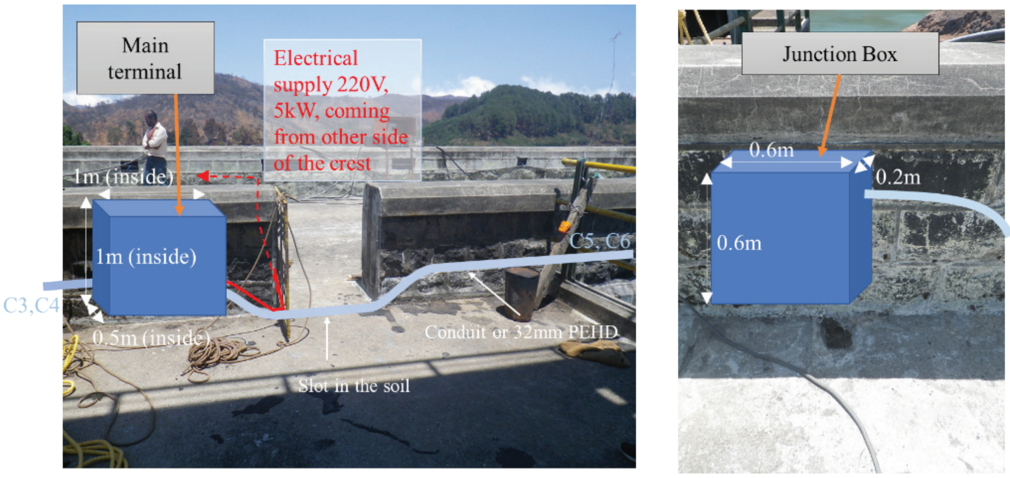

Figure 9 : Shelter for Optical connections on the crest

The cables will be heated at approximately 6 W×m^{-1}, using an electrical supply of 5kW (220V) available for the command box. According to the methodology validated during 2018 tests (Guidoux 2019), the measurements will be performed:

- before the impoundment of the dam (reference);
- each year or in case of increasing leakages measured in the drainage gallery.

3.3 Installation

The installation started in May 2019 and carried on till mid June 2019 when monsoon started and the work is now extended to the next season. In the current situation, the entire installation of geomembrane has been planned in two phases. The entire dam has been divided into 4 segments (Top Left, Top Right, Bottom Left and Bottom Right). While the Top Left (20%) has been completed in the year 2019 between May 2019 and mid June 2019, the remaining portion is planned for installation between March 2020 and mid June 2020. Wherever the cables are required to be positioned, the following sequence of works are being carried out.

The installation of the cables progresses as described below:

- upstream face preparation
- installation of the cable protection geonet
- installation of the cables on the vertical paths between the crest and the location of the boundary between work phases, with preserved extra length at the top and the bottom
- fixation of the cable every 2 meters (Figure 10)
- reading of metric inscription on the cables in order to identify any measurement point on the cable
- installation of the geomembrane
- quality controls (optical continuity, integrity of the cables)
- pulling of the upper cable ends into their shelter
- protection of the lower end of each cable until the next work phase

Figure 10 : From Left to right, Fiber Optic cable positioned above the geotextile, geogrid protecting the fiber cable and an external protective pipe covering the exposed optical fiber cable at the crest

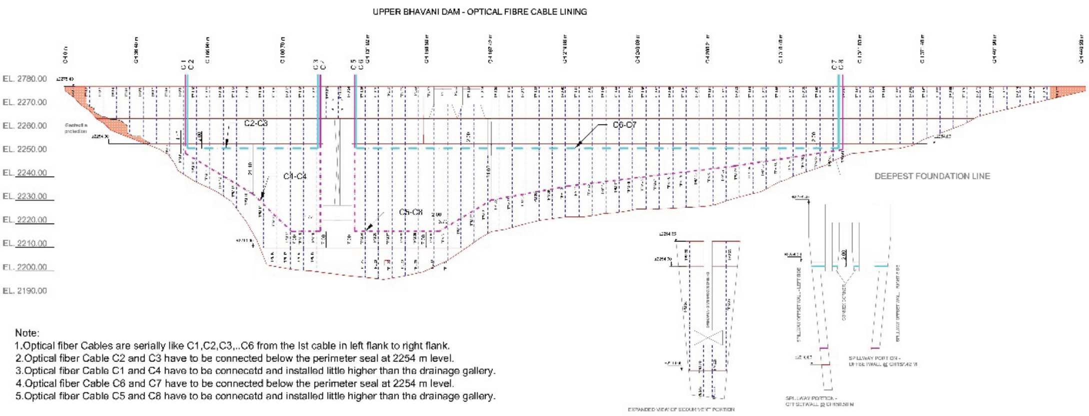

Figure 11 : Position of the Optical Fiber Cable along the entire periphery of the dam

3.4 Future works

In the second season programmed to begin in March 2020, the optical fiber cables will be positioned in the vertical section between the crest and the position where the cable takes a horizontal path. Wherever there is a break in between two seasons of work a special connection box will be provided to ensure connectivity between the two sections of the cables.

3.5 Cost

The entire scope of work is designed and getting installed well within the contractual price as stated in the agreement. The success of this project in Upper Bhavani is largely attributed to the meticulous design and planning of the fiber optic system in such large dams.

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