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Leaks detection of earthwork dam with geomembrane lining system by an active technique using optic fibers

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ABSTRACT: This article presents the development of an active optical fiber device to address the issue of leak detection, and to allow operators to monitor the performance and safety of mountain reservoirs sealed with geomembrane lining systems. The device includes a fiber integrated into the geomembrane lining system and devices to heat and auscultate the fiber. The results shown that the active method has been successfully applied in a representative INRAE demonstrator. In particular, it has been shown that the technique is capable of locating without false positives or negatives a leak with a flow rate greater than or equal to 0.05 l/s and placed upstream of the optical fiber.

1 INTRODUCTION

The performance of geomembranes for sealing hydraulic structures such as basins or reservoirs no longer needs to be demonstrated. However, despite the robustness of geomembranes, the presence of leaks through them is possible. From some assumptions about frequency of holes per square meters, Giroud and Bonaparte (1989) gave some assessments about the leakage rates through a geomembrane liner. These leaks may appear during the construction of the hydraulic structure or during the service phase of the hydraulic structure. Leaks from construction work may be due to welding defects or damage to the geomembrane. They can be drastically avoided by a rigorous quality assurance construction program and by applying weld quality control methods (vacuum bell method, pressurizing the central channel method, etc.) and electrical leak detection methods such as the use of the water lance method/water puddle method electric broom (Touze et al., 2021; Müller, 2007). During the operation phase of the structure, leaks may appear due to the application of static loads by puncturing aggregates in contact with the geomembrane (below or above it), or else by the application of dynamic loads (eg a falling block) on an exposed geomembrane. In the case of an exposed geomembrane, the location of a leak can be done visually (if the basin is empty) or with an electrical geophysical method (if the basin is filled). In the case of a geomembrane covered with a layer of granular materials, the detection and location of a leak that appeared during the service phase of a basin is less obvious by the methods mentioned above. However, there are basins for which it is important to detect and locate a leak very quickly to ensure safe use of the structure. This is for example the case of altitude reservoirs which are the type of structure targeted by the study of this article.

Hill or altitude reservoirs are hydraulic works mainly dedicated to the production of artificial snow (main purpose of altitude reservoirs) and / or intended for irrigation (main purpose of hill reservoirs). Other applications are possible such as the production of hydroelectric power, the supply of drinking water, as well as for the practice of leisure fishing. The storage capacity of altitude reservoirs is variable, ranging from modest capacities (less than 20,000 m³) to significant capacities for altitude structures (greater than 150,000 m³). The RISBA project (2013 - 2015), "Risks of high altitude dams", has shown that the majority of recent or planned reservoirs have

an average capacity of around 100,000 m³ (Boutry et al. 2014). In France, the height of the embankments (i.e. the difference between the crest and the natural terrain) of the altitude reservoirs is between a few meters up to a maximum of 19.95 m, which, compared to their storage capacity, theoretically corresponds to administrative classes C and D. In Italy, in the Aosta Valley, almost all these types of structures have backfill heights comprised between 10 m and 15 m. Even if the size of the altitude reservoirs is modest compared to large dams, given the severe meteorological conditions in winter at an altitude above 1800 m (Peyras & Meyriaux, 2009) and their potential impact in the event of failure, these structures are frequently administratively upgraded (transition from theoretical class C to class B).

Regarding the design of the altitude reservoirs, with the exception of the oldest ones, the majority of these structures have a geomembrane lining system (GLS). In addition to the geomembrane which ensures the waterproofing function, this type of device comprises several layers each providing one or more functions such as the support structure (on which the geomembrane is set and having functions of protection and drainage of the geomembrane) and the structure protection, overlying the geomembrane, which has a role of protecting the geomembrane against external mechanical stresses. A full description of GLS can be found in Peyras & Meyriaux (2009).

In general, the presence of a leak in the structures described above is detrimental and, in extreme cases, can seriously affect the stability of the structure. Thus, to ensure the stability and ensure the durability of the structure over the long term, any leak must be located and repaired. In the case of a covered geomembrane, generally by a multi-decimetric granular layer, the presence of a leak is dramatic because it is necessary to remove the entire layer of aggregates to access the geomembrane and perform the visual inspection and reparation. It is then obvious that this operation is long and potentially detrimental for the geomembrane because the machine which will remove the granular cover layer can itself damage the geomembrane again.

In this context, a specific action on the development of a simple and robust method for locating leaks was carried out within the framework of action WP3.4.1 of the European research project Interreg Alcotra called RESBA, "resilience of dams d'altitude", started in 2017 and bringing together French partners (INRAE and the University of Savoie Mont Blanc) and Italian partners (Piedmont and Aosta Valley region, Polytechnic School of Turin). This action consisted of testing the active method by optical fiber, in an optimal configuration for this type of structure. Although the method is already operational (for example Guidoux et al., 2019 tested successfully a close method on a concrete experiment dam), there are currently no altitude reservoirs equipped with such a device. This observation can be explained by several possible reasons: lack of knowledge of the technique by the administrator of altitude reservoirs, absence of a demonstrator at the site level, negative prejudice concerning the difficulty of transport and the cost linked to the heating generator to take away in mountainous context, etc.

To demonstrate the performance of the method under conditions close to a real structure, the method was implemented through geophyConsult on the experimental basin of the INRAE site in Aix-en-Provence. Three main questions were particularly investigated:

- What is the minimum (heating) power to be supplied for optimum leak detection?
- What is the minimum leakage rate detected for minimum heating energy? This question is particularly linked on the one hand to the detection criterion, i.e. the temperature difference which can only be explained by the presence of an anomaly (i.e. a leak), and, on the other hand, at the distance of the leak relatively to the positioning of the optical fiber;
- Is the system as efficient in hot period (summer) as in cold period (winter)?

2 BACKGROUND OF THE ACTIVE METHOD BY OPTICAL FIBER

2.1 *The active method*

From the first leak detection experiments using fiber optic temperature measurements carried out from 1995, it appeared that the visualization of raw measurements only usually did not allow to identify leaks correctly. Indeed, many factors other than leaks influence the temperature of a soil: the geological nature of the soil, the relative position of the fiber with respect to the air or the upstream reservoir, or even the proximity of crossing structures. The development of methods for

analyzing temperature data by optical fiber therefore quickly turned out to be a major challenge in making this technology operational.

The active method or Heat Pulse Method (HPM) Dornstadter J. &, Heinemann (2010) is mainly used in cases where the optical fiber must be installed in an environment whose temperature is directly influenced by the water in the reservoir (even with no leakage). It refers to the realization and use of temperature measurements within an optical cable installed near the reservoir and previously heated by the Joule effect using electrically powered copper wires (see Figure 1).

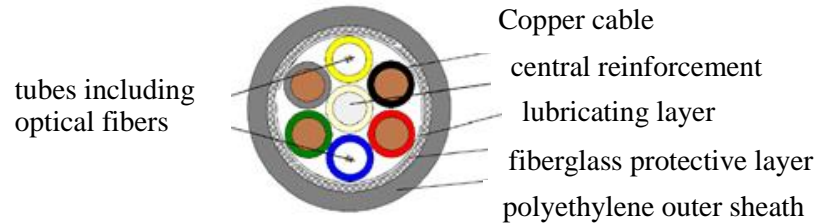


Figure 1. Optical cable used for the active method.

The needed electrical power - typically 5 to 10 W/m - depends on the conductivity of the soil, the heating time and the aimed temperature increase. In the presence of a leak in the vicinity of the cable, the convection generated by the flow will cause a lower rise in the temperature of the cable (see Figure 2).

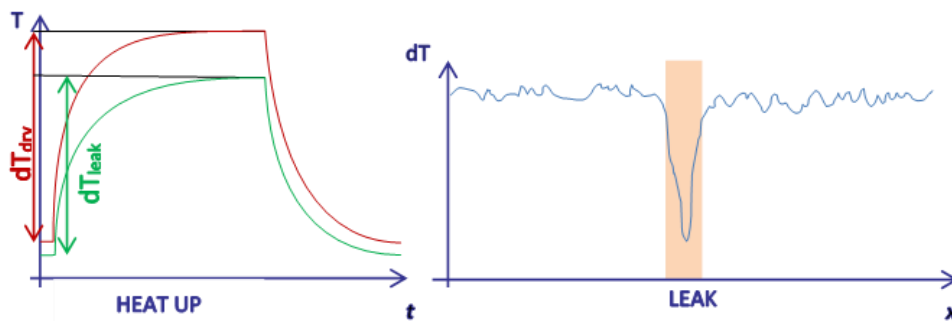


Figure 2. HPM principle.

2.2 Interpretation and outcomes

The interpretation of the measurements is based on the comparison of the measured values of dT with a reference value of dT_{REF} . Through calibration tests in the laboratory or on site with controlled leaks (Perzmaier, 2007), it is possible to quantify the flow velocity for a range of Darcy's velocities between 10^{-5} and 10^{-3} m/s. The leak detection radius around the optical cable using this method is often less than for passive approaches, in the range of 15 to 20 cm. The means required for heating make this method more difficult to operate on measurement lengths of ten kilometers or more.

As some technical parameters may vary from one heating to another (the injected electrical power, the heating time, the evolution of the outside temperatures), the raw dT profiles are systematically readjusted, by adjusting their average and their standard deviation to those of a reference measurement. The dT values of a given heating are then subtracted from the dT_{REF} values recorded at the same positions during the reference heating. A measurement is thus obtained at any point of the cable which is strictly speaking the detection parameter of the active method, to which a detection threshold depending on the field conditions (spatial variability characteristic of the cable used) is applied. This methodology is called SACRE (as for Surveillance Active par "Centrage et Réduction avec Etat-zéro" in French, Active Monitoring by Centering and Reducing with Reference-State).

3 MATERIAL AND METHOD

3.1 Design and realization of the experimental basin

For the experiments, a basin already existing at INRAE's site of Aix-en-Provence was completely redesigned in order to fit the topic of the research (Figure 3). The embankment delimiting the basin is 23m long and 10m wide; it is made of local clay, which Plasticity Index is 17 and hydraulic conductivity is $10^{-9}\text{m}\cdot\text{s}^{-1}$. The dike is 2.5m high, so the water head is about 2m.

In 2019, we added a new GLS to the structure: first, a DRAINTUBE® drainage geocomposite made up of mini-drains with a diameter of 20mm spaced 2m apart is installed directly on the soil; drains are parallel to the slope and connected to a central gravel drain that allows evacuating water supplied by the leaks. Then, a 1mm thick polypropylene geomembrane placed above the geocomposite ensures the waterproofness.

Fourteen artificial leaks cross the geomembrane and bring water between the two geosynthetics; water is collected by the mini-drains. Each leak is connected to the water supply through a garden hose; water is directly pumped into the basin to have the same temperature as the basin water. The leaks reproduce the potential geomembrane damages, and are located on the basin in order to study the influence of sun exposure and their relative position to the mini-drains. Sensors and valves are used to control and measure pressure and flow rate of the leakage water.



Figure 3. View of the experimental basin.

3.2 Instrumentation of the basin

The purpose of this basin is to process real-scale measurements with controlled conditions. Therefore, we have installed a large panel of instrumentation inside out of the embankment (Figure 4).

3.2.1 The leaks

The leaks are part of the instrumentation and the reservoir is composed of fourteen leaks. Each leak is connected to a garden hose and pierce artificially the geomembrane (Figure 5). Water from the basin supplies directly the leaks using a pump (Lowara BGM9). The leaks allowed the water to pass through the geomembrane, then the water will be collected by a mini-drain in the DRAINTUBE® drainage geocomposite and led down to the bottom of the basin.

Leaks are spread through the surface of the basin in order to study the influence of the sun exposure and their relative position to mini-drains.

3.2.2 The active optical fiber

The optical fiber is composed of a measurement cable and a compact optical interrogator device (Sensornet Oryx). During the second campaign, this interrogator was kindly loaned by EDF through geophyConsult. In this experiment, the optical fiber is associated with few copper cables rolled along the length of the cable (Figure 1). The copper cables were used to heat up the optical fiber; this combination, which allows the fiber to contrast clearly with its environment, is called the active optical fiber. The electrical power injected during the heating operations was recorded with an energy consumption meter (Voltcraft Energy Logger 4000F), placed upstream of the heating device.

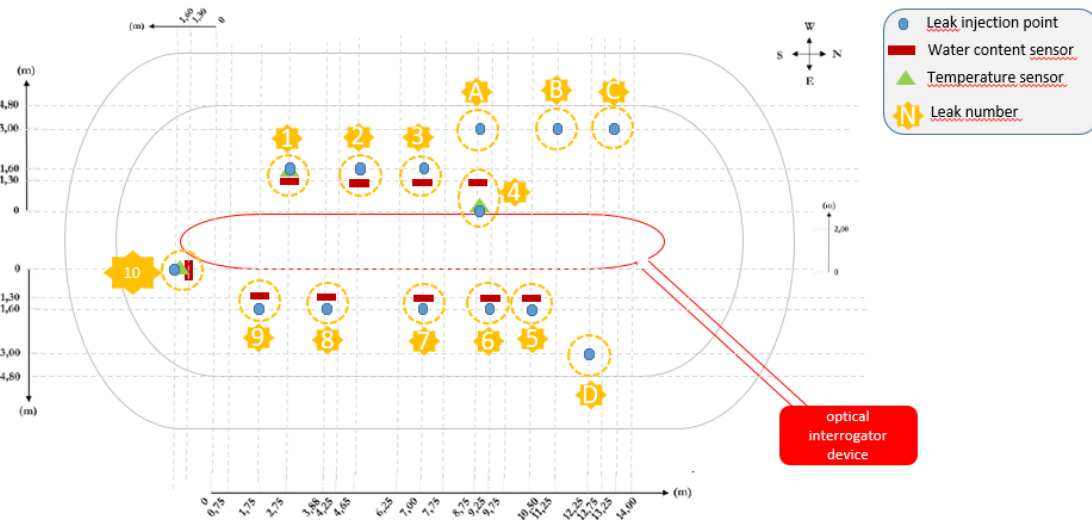


Figure 4. Instrumentation plan, view of the basin from above.



Figure 5. Leaks insertion system.

During the measurement campaigns, the active optical fiber was used as a temperature sensor with a spatial resolution of 1 m and a 5 minutes acquisition frequency. The active optical fiber is located at the bottom of the basin under the drainage geocomposite (Figure 4 & Figure 6).

The detection of a leak by the optical fiber corresponds to a calculation of the temperature difference measured in the vicinity of the optical fiber in the absence of a leak with that measured in the presence of the leak. This parameter is denoted ΔT . The criterion for detecting a leak, corresponding to a measured thermal anomaly, was set at 0.3°C . For the purpose of quantification, the detection intensity ($^{\circ}\text{C}\cdot\text{m}$) is calculated, which corresponds to the area under the curve ΔT along the linear optic fiber.



Figure 6. Localization of the active optical fiber.

3.2.3 Measured and controlled parameters

Temperature and water content probes located downstream of the leaks (Figure 4) are used to confirm fiber optic measurements. Three temperature sensors (Probe 107 Campbell Scientific) were used to measure the temperature of the water near the leaks (Figure 4).

Ten water content probes (CS650 Campbell Scientific) were installed to detect the water streaming down from each leak. A CR1000 data acquisition system (Campbell Scientific) recorded the set of data from temperature and water content under a 1-minute acquisition frequency.

The incoming pressure (Jumo Dtrans p30 type 404366 sensor) and the flowrate (Kobold MIK 5NA 55 E L443 sensor) of each leak are controlled with a valve placed upstream and recorded during the experiments with a USB-6001 data acquisition card (National Instrument).

3.3 Experimental campaign

The experimental basin was subjected to two experimental campaigns of 5 days of measurements: the first was carried out from October 11 to 21, 2019 and the second from February 10 to 14, 2020. The objective of these two campaigns was on the one hand to test the performance of the device during two periods when the outside temperatures are different and, on the other hand, test the robustness of the device over time, on the scale of a research project. During the injection campaigns, five injection flow rates (0.005 - 0.01 - 0.02 - 0.05 - 0.1 l/s), 5 heating powers (2 - 4 - 6 - 8 - 10 W/ml) and three distances injection point - heating cable (0 - 1.6 - 3.0 m) were tested. Each of the heating powers has been the subject of a reference measurement, that is to say a measurement of temperature rise in the vicinity of the optical fiber and the heating cable, in the absence of leaks.

4 RESULTS AND DISCUSSION

It has been shown that all the leaks with a flow rate greater than or equal to 0.05 l/s and placed upstream of the optical fiber at the base of the backfill have all been detected. With the detection criterion of 0.3°C, and with a heating power greater than or equal to 4 W/m, no false positives were detected.

No significant impact of heating power on leak detectability was observed. In other words, a leak detected with a power of 8 W/m was also detected with a power of 2 W/m. However, the use of a low power induced false positives caused by the too low temperature contrast induced by the heating. Consequently, a minimum power of 4 W / m is recommended.

Increasing detection intensities were observed with the injected flow rates (Figure 7). At equivalent flow rate, the detection intensities decrease if the distance between the leak and the measurement cable increases, in line with the fact that the leakage speed decreases along the propagation of the leak (diffusion in the drainage geocomposite). Thus, on a real site, it is recommended to install optical fibers at several sides of the basin, with a spacing which will depend on the desired level of leak detectability.

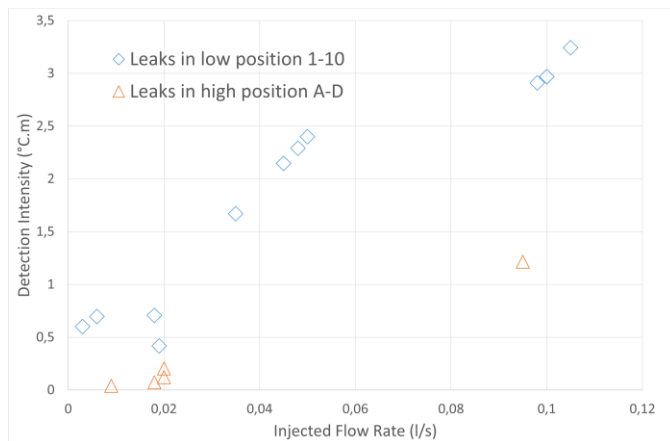


Figure 7. Detection intensity as a function of the injected flow rate.

5 CONCLUSION

The purpose of this article was to implement a method for locating and detecting leak in GLS via an optical fiber positioned just under the geomembrane. In the fiber optic cable is integrated a copper cable to heat the environment close to the fiber. This heating makes it possible to create a thermal contrast and to evaluate more precisely the zones of leaks compared to all the normal zones, that is to say without leaks. This device finds all its interest in critical basins, as is the case for high-altitude reservoirs. This device has been successfully applied in a representative INRAE demonstrator.

It has been shown that the technique can locate without false positives or negatives a leak with a flow rate greater than or equal to 0.05 l/s and placed upstream of the optical fiber. However, as the level of leak detectability depends on the distance between the leak and the optical fiber, the sizing of the optical fiber network to be positioned in the structure will be a key step in the performance of the device.

6 ACKNOWLEDGMENT

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