Thermal Monitoring of Embankment Dams by Fiber Optics

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Abstract

Internal erosion is the main cause of failure of earthen hydraulic structures. Moreover, it is often difficult for the operator to detect internal erosion at an early stage.
For the last twenty years, leakage detection by thermometry has been developed mainly in Europe. The principle is based on the fact that a leakage through an embankment dam changes its temperature field.
In this regard, fiber optics buried in the structures can be used as temperature sensors. Their principal advantage is distributed temperature measurements, at every meter along their length, and over long distances. Indeed, once deployed, optical fiber proves to be an effective mean of probing several kilometers, making it extremely useful for monitoring dikes.
Various methods have been developed for analysis of temperature data acquired by these powerful sensors. These physico-statistical and signal processing methods allow to propose a system for "early warning" or for long-term monitoring.
Based on the results of several tests at controlled and industrial sites, this presentation will demonstrate the improvement of this surveillance methodology for the safety procedures of embankment dams.

Introduction

Erosion of hydraulic embankments like dams and dikes, specially the internal erosion, constitute the principal risk to the failure of these structures. In this regard, EDF is particularly concerned to ensure the safety of the dikes which enclose inlet canal of its numerous hydraulic stations. The thermal surveillance of these structures using optical fiber sensors is an area in which EDF and his partners have been developing their expertise for some time. Several methods for analysis of temperature measurements have been developed in order to detect leakages, precursors of internal erosion.
After introducing the principle of internal erosion detection by distributed temperature measurements along fiber optics, this paper presents the real performance of the physico-statistical and signal processing analysis methods used as either alarm or monitoring system based on experimental and real sites results.

Internal erosion detection by fiber optics

In the studies related to the failure of embankments, internal erosion has been identified as one of the principal causes leading to failure [1]. Internal erosion corresponds to the movement of soil particles under the influence of significant flow through a dike.
Amongst other, temperature is one of the most important physical parameters directly related to internal erosion. Thermometry is thus potentially a very useful tool for early identification of leakages which eventually lead to internal erosion. The underlying principle is that in the absence of leakages, temperature changes are driven by the phenomenon of conduction. The occurrence of a localized leak results in an additional source of temperature change by convection, and thus the temperature measurements are driven by the superposition of these two phenomena.
The distributed temperature sensors, based on Raman optical fibers, allow probing the entire dike lengths with high spatial and temperature resolutions [2]. The ranging length can go up to 30 km with the temperature resolution decreasing with an increase in the ranging length. Moreover, they allow continuous monitoring over long periods of time with efficient temporal resolutions.
In order to monitor the leakages over long periods and distances, the distributed temperature sensors, based on optical fibers, provide an efficient solution, with their capability of giving a global view as well as a detailed local view of the inspected site [3].
Burying the fiber at a strategic location in the dike (e.g., at the toe end of downstream), we could intercept the changes in temperature (Figure 1). A leakage would bring about changes in local thermal conditions which would be detectable by the temperature measurement system with the help of distributed fiber optic sensors.

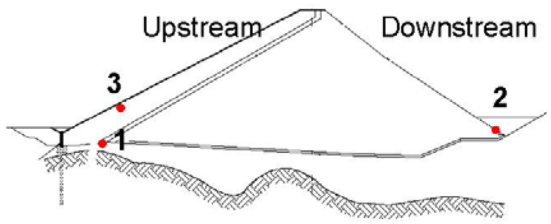


Figure 1: Example of fiber optics location in a homogeneous dam with a concrete face

1. In the drainage system, for new dams
2. In the toe on the downstream face, for existing dams
3. Behind the concrete face, for new or existing dams (during works)

However, talking of a continuous monitoring system at an installation site, the signature of leakage would not necessarily be immediately discernable in the raw temperature data. This is due to the fact that the acquired temperature data could be influenced by other external factors. In order to eliminate their influence, so called “active” thermometric measurements can be effected which comprise observing the dynamics of temperature along an electrically heated optical fiber [4]. However, this system, used over shorter distances (> 2km), requires high electric power (e.g. around 3 to 15 W/m) and is not always cost effective in terms of monitoring. For long-term analysis, the so called “passive” method would thus be employed which is a natural measure of temperature [5]-[8].

Consequently, in order to exploit the thermometric data acquired with passive measurements, a detection system would be required with the aim of separating the leakages from other perturbing phenomena. In this regard, various methods, based on physico-statistical and signal processing analysis, could be used as a system of leakage detection.

The detection system developed by EDF is based on the analysis of daily raw temperature data by dissimilarity approach [8] for early warning system and of monthly raw data by source separation approach [9] or annually by impulse response model [6], for long term monitoring.

These analysis models have been validated on several experimental and real sites, as presented in the next sections.

Early detection of piping erosion: Ijkdijk test

The 2009 project IJKDijk was launched in order to study the phenomenon of piping erosion in particular, and for the surveillance of dikes to test new sensor technologies in field conditions.

Four experimental full-scale dikes were constructed and put under charge by filling the reservoirs with water in order to provoke significant flows through the dikes and the measurements were recorded until failure. The experimental embankments, 15m long and 12m wide, were built with a height of 3.5m and slopes of 1:2. The fiber optics were incorporated in these dikes during their construction. The cross-section of a typical experimental dike is shown in figure 2, whereby the dike is constructed with clay on a sand base which in itself was saturated before reservoir filling.

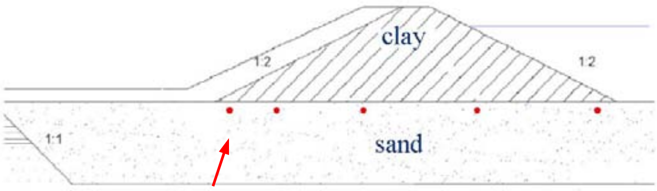


Figure 2: Cross-sectional view of the dike for a typical experimental phase showing the dike composition and placement of the optical fibers.

The experiments lasted approximately 4-6 days. In this application, the thermometric data were analyzed using a daily analysis methodology. Then, the analysis results are compared to observed water outlets from the continuous visual inspection carried on the downstream toe of the dike. In this paper, we will focus on the analysis results from the raw temperature data measured with the fiber optics placed on the downstream toe (indicated by the red arrow in Figure 2) during the second test.

Test 2: example of results from Ijkdijk piping test

The reservoir was filled on 19th october, 2009 at 12 h00, and the experiment was stopped on 25th october at 10 h00 following the subsistence of the dike crest. The maximum charge imposed on dike upstream was 1.9 m.

The data considered for analysis here are those acquired between 19th october at 9h18 and 25 october 9h10. During this period, the raw temperature data visualization proposed by [11] allowed the detection of precursors to the dike failure 2 days in advance considering that the overall experiment duration was about 6 days.

Results of temperature data analysis

It can be observed that the analysis on the first day (Figure 3) does not reveal any anomalies of significant magnitude. However, from 20 october onwards (2nd day of experiment) until 23 october, considering the results from Figure 3 reveals presence of a strong anomaly around 9m, corresponding to a leakage zone at the downstream face of the dike identified through visual inspections at the site. Other anomalies, albeit with small magnitudes, can also be identified (particularly the one around 14 m).

Owing to the sharp augmentation of detection indicator for the last two days of analysis, their results are presented on a different scale in Figure 4. Strong dissimilarities are once again observed for day 5 (23-24 oct.).

Finally, during the last day of analysis on 24-25 october, the

influence of the anomalies is extended over a large part of the profile thereby resulting in identification of several strong magnitude locations.
The increase in the magnitude of the detection parameter can be attributed to the increase in the flow rate of the leakages.
The analysis approach allows detection of anomalies as early as the second day of experiment, i.e., 4-5 days before the eventual dike rupture for the test which lasted a total of 6 days.

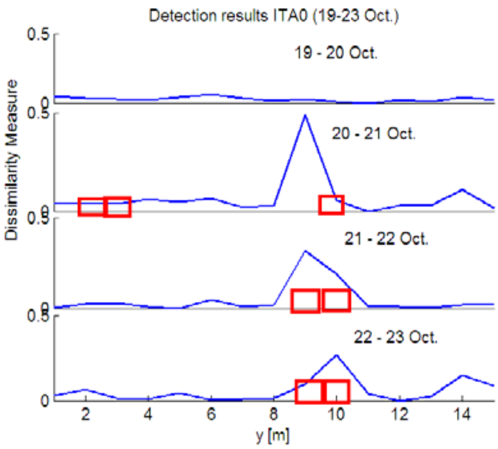


Figure 3: Analysis results (19-23 oct.) for test #2 for the optical fiber placed at the downstream. Red rectangles represent leakages observed through visual inspections.

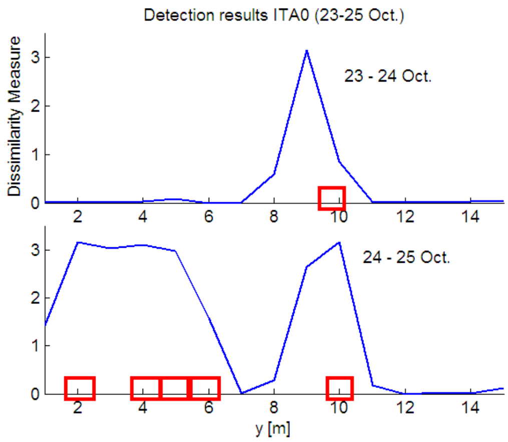


Figure 4: Analysis results for test #2 for the optical fiber placed at the downstream for last 2 days (23-25 october). Red rectangles represent leakages observed through visual inspections.

The results presented uptill now were based on the analysis of daily temperature variations at all the distances. The resulting detection parameter thus has a resolution in time of 24 hours and in space of 1 m. However, it is possible to improve the temporal resolution using the sub-daily analysis (12 hour) with no significant variation of the overall computational time (Figure 5). The different leakages can be resolved at a 12-hour level in terms of their appearance and disappearance. Considering for example the last day of analysis (24-25 october), the leakages at 2 m, 4 m, 5 m, 6 m and 10 m are efficiently resolved with the diminution of detection parameter for 10 m leakage in the last 12 hours and appearance of leakages at 2 m. The significant flow of water through the dike shifts more towards 4-6 m in the last 12 hours.

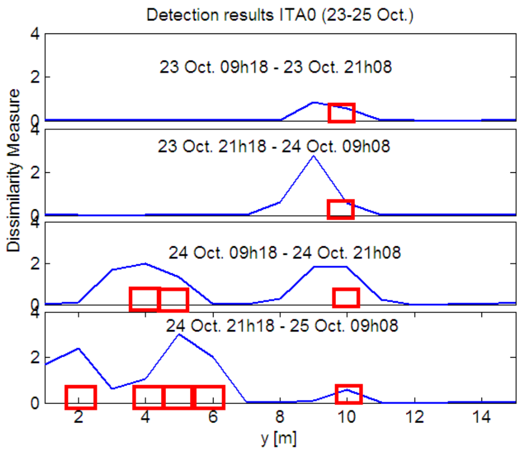


Figure 5: 12-hour analysis results for test #2 for the optical fiber placed at the downstream for 19-25 october. Red rectangles represent leakages observed through visual inspections.

Numerous flexible derivatives of the analysis methodology can thus be adopted depending on the system requirements, such as 12-hour analysis with sliding windows of some hours overlap. This gives potentially a very potent analysis tool capable of serving as real-time alarm system.

Long term monitoring of leakages: real site

In order to validate both analysis methods used for long term monitoring of dams (i.e. source separation model and impulse response model), we applied them on raw data acquired in 2007 on an industrial site from EDF, instrumented using 1km of fiber optics.
This site is located in the north of France, a continental climate. The fiber optic cable is buried at the intersection of the embankment slope and surface of drainage canal (Figure 6). Periodic visual inspections have led to the presence and rough localization of leakages, changing seasonally over a large part of the dike.

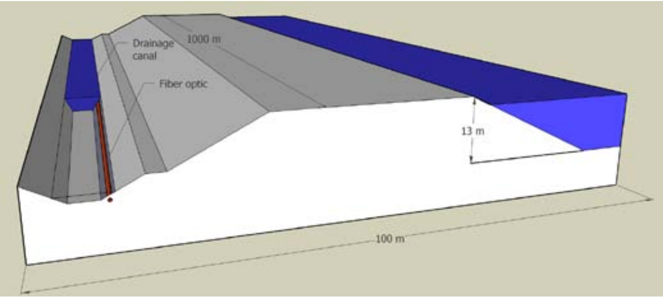


Figure 6: Representation of the global view of the instrumented dike of EDF.

Results from the impulse response model

The impulse response method is tested over a measurement period of 1 year. This analysis allows to identify several suspected areas which could correspond to leakage zones. Moreover, the presence and the localization of these suspected zones depend on the season (Figure 7). This observation is in accordance with the the frequent visual inspections.

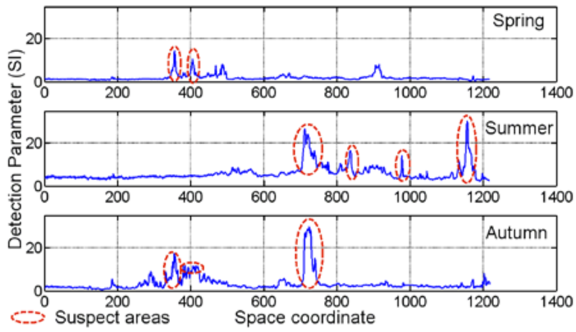
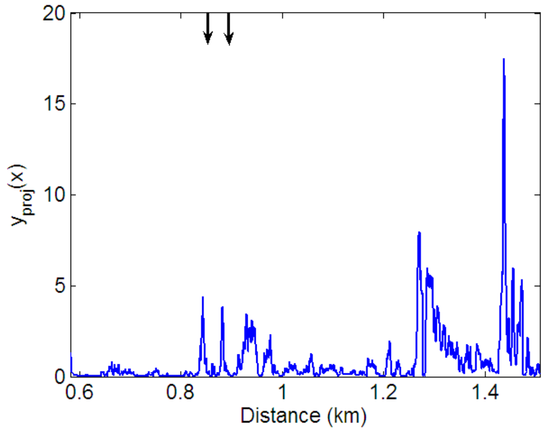


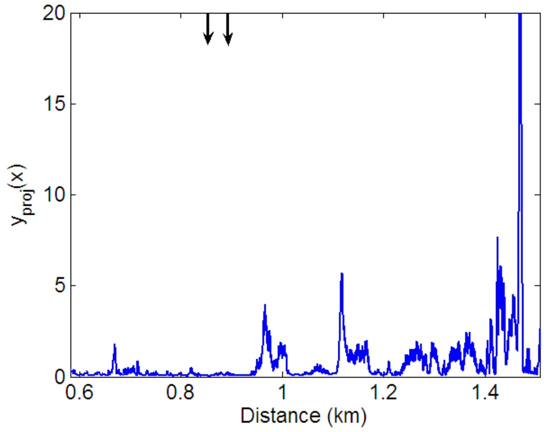
Figure 7: Results from the impulse method applied on the 2007 data.

Results from the source separation model

The detection results using the source separation approach are shown in Figure 8 in terms of the projection $y_{proj}(x)$ of the detection parameter during the months of april and july, 2007. Different anomalies were observed for this experimental site, which corroborate quite well the visual inspection results. Moreover, as previously observed, the leakages show evolution over the course of time. This can be observed by the positions marked with arrows where the anomalies present in april (Figure 8a) disappear in july (Figure 8b).



(a) April, 2007



(b) July, 2007

Figure 8: Results from the source separation based detection method for the 2007 data.

Seasonal variation of leakages

The field observations and the results from thermal fiber optics monitoring show that certain leakages appear and disappear over the course of time. This is a peculiarity of the site under consideration. Moreover, the flow rate of the leakages observed in the downstream toe is very small. The appearance or disappearance of these leakages could be explained by the plugging or unplugging of these paths by fine particles of soil. During seasonal flood events, the transport of fines by the river is more important. This could explain the seasonal frequency of leakage occurrences.

Consequently, in view of these observed changes in hydraulic behavior of the structure, the choice of the temporal analysis window appears to be an important parameter for monitoring long-term behavior. The flexibility and the richness of the analysis methods can be exploited in this regard to obtain useful interpretations of the long term behaviour.

Conclusion

Internal erosion is one of the principal causes of dike failures and affects the thermohydraulic behaviour of embankments, i.e. the seepage flow rates and temperatures. Due to the convection phenomenon, dam temperatures are highly sensitive to leakages. Thermal monitoring is an effective tool to detect leakages in dikes. Distributed temperature measurements along buried fiber optics allow the surveillance of large dike sections with a high spatial resolution.

The analysis method developed by EDF, based on physico-statistical and signal processing approaches provide an efficient solution for dike surveillance., This multipurpose system is capable of serving both as an early warning system, owing to the fact that it is automatic and allows measuring the anomalies well before they are physically visible, and a long-term monitoring tool.

This paper validates the utility of the analysis method over the visualization of raw temperature data and demonstrates the performance of these analysis methods on a controlled as well as an industrial site. The thermal monitoring of hydraulic structures using the fiber optic sensors is a novel, powerful and cost-effective tool, ensuring their safety.

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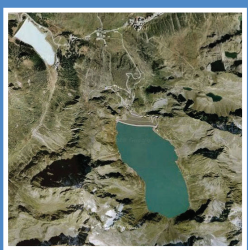



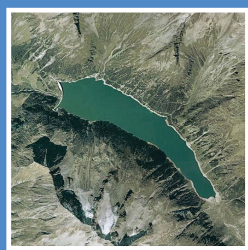
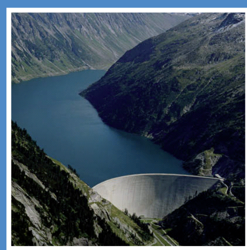

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