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► **To cite this version:**

Amir Ali Khan, Pierre Cunat, Yves Laurent Beck, Jerome I. Mars, Valeriu Vrabie, et al.. Distributed fiber optic temperature sensors for leakage detection hydraulic structures. WCSCM 2010 - 5th World Conference on Structural Control and Monitoring, Jul 2010, Tokyo, Japan. pp.10071. hal-00539714

HAL Id: hal-00539714

<https://hal.science/hal-00539714>

Submitted on 24 Nov 2010

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DISTRIBUTED FIBER OPTIC TEMPERATURE SENSORS FOR LEAKAGE DETECTION IN HYDRAULIC STRUCTURES

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Abstract

Structural health monitoring of civil engineering infrastructures like dams and dikes is a vital issue because of their harsh working environments. It is inevitable to detect all kind of anomalous behavior in order to take preventive measures well in advance. Most of the failures in the embankment dams are attributed to internal erosion, the movement of soil particles under the influence of significant water flow thorough the structures. This significant flow in turn brings about a change in temperature of the structure thus making temperature a very useful measurand, containing information about leakages. The conventional techniques for surveillance of dikes are comprised of visual inspections and local measurements carried out punctually. However, subject to the constraint that these structures are spread over large distances (several tens of kilometers), semi-autonomous methods have to be employed. Distributed temperature sensors based on optical fibers present an economically viable solution in this regard. The low-cost telecommunication fiber, serving as an intrinsic sensor, is probed to obtain temperature profiles with high spatial (1 m) and temperature resolutions (0.01 to 0.1 °C). The raw temperature data being not immediately interpretable in terms of leakage detection, requires subsequent intervention of analysis techniques. In this paper, we would present the analysis methods based on advanced signal processing techniques such as source separation as well as several case studies on real experimental sites of EDF (major dam owner in France) which have successfully allowed water leakage detection.

Introduction

Hydraulic structures like dams and dikes which continuously surround water are always at risk because of severe environment, internal erosion, ageing, ground movements, etc. For dam owners like Electricité de France (EDF), the surveillance of these structures assumes a very high priority. Efficient surveillance solutions have been developed over the years for taking pre-emptive actions to avoid a possible rupture. About 50% of the total dam failures reported are attributed to *internal erosion*, movement of soil particles under the influence of a significant flow through the structure (Fell *et al.*, 2007). Internal erosion is usually identified by the presence of water leakages. Although, soil parameters like resistivity and permeability are implicitly linked to internal erosion, temperature offers a more explicit link (Johansson, 1991). The sensitivity and reliability of temperature measurements for identification of significant flows in the embankments is well established in literature (Kappelmeyer, 1957, Armbruster *et al.*, 1989, Fry, 2004).

The fact that dikes constitute structures spread over several kilometers together with continuous monitoring requirements imposes the constraint of semi-autonomous systems. The distributed temperature sensors (DTS) based on fiber optics present an efficient solution in this regard. The idea is to develop monitoring systems capable of generating automatic alerts with centralized control in order to complement the existing auscultation methods like visual inspections. The possibility of multiplexing a large number of sensors on a

single optical fiber and the flexibility of sensor placement are some of the unrivaled advantages of DTSs. Moreover, their long-range measurement capability (up to 20 kms) and efficient spatial (1 m) and temperature (0.01 to 0.1 °C) resolutions give them distinct advantage over conventional sensors.

The temperature measurement method using DTS, considered in this paper, is the so called *passive method*, a natural measure of temperature. In the absence of anomalies, the measurements are driven by phenomenon of conduction: the heat transfer is attributed to the interaction between air temperature and temperature of water naturally present in the ground. Leakage resulting from water flow through the dike brings an additional heat component driven by the phenomenon of convection. Thus, when convection superposes conduction, the temperature measurements can help in leakage detection. The fiber optic, buried at a strategic location inside the dike (e.g., at the downstream toe), can therefore intercept the temperature changes. The change in the local thermal conditions due to leakage is captured by the fiber optic based DTS. However, for real on site installations, the leakage signature is not the only factor influencing the acquired temperature. Other environmental factors, like existing structures (drains), self-response of the ground in which the fiber is buried, seasonal temperature variations, ground heterogeneities, precipitation, etc, can equally influence the acquired data. In brief, the recorded temperature data are not immediately exploitable in terms of leakage identification and thus require intervention of analysis methods.

This paper would focus on the methods based on advanced signal processing techniques exploiting only the temperature acquired by the fiber optic without any a priori whatsoever. Two approaches were developed in this regards, a medium-term analysis approach based on source separation techniques (Khan *et al.*, 2008a) and a daily alarm approach based on singularity detection (Khan *et al.*, 2010). This paper aims at presenting some case studies of application of these approaches on real instrumented sites in France. The analysis methodologies would therefore only be briefly recalled and the interested readers can refer to the cited references. The paper starts with a description of temperature data acquisition system using fiber optic sensors followed by a brief exposition of the proposed leakage detection methodologies. Finally, the results of their application on different experimental sites are demonstrated.

System Description and Data Model

Figure 1 illustrates a typical installation of fiber optic at the downstream toe of the canal, being interrogated by a distributed temperature sensing device placed in instrumentation room. The commercial DTSs are based on Raman backscattering principle using the optical time domain reflectometry (OTDR) (Hartog, 2000). The major components of the sensing system are: a pulsed laser source, a directional coupler and an optical fiber cable serving as an intrinsic temperature sensing element. The interrogation principal is very similar to that of radar. The light photons emitted by the laser source interact with the molecules of the fiber material. Some of the photons are backscattered by the thermally induced molecular vibrations, attributed to Raman scattering. The Raman spectrum consists of two backscattered components, at equidistant frequencies around the incident frequency. The intensity ratio between the temperature dependent Anti-Stokes and temperature independent Stokes components gives the temperature as a function of arrival time at fiber input. Knowing the speed of light inside the fiber, the temperature along the entire fiber length can be obtained with a pre-defined resolution.

The principal advantages of DTS over conventional sensors include their commercial viability, long-range measurements, efficient spatial and temperature resolutions, ruggedness and immunity to electromagnetic interference, etc. There exists a trade off between different parameters of DTS device like spatial and temperature resolutions, speed of measurement, range, signal to noise ratio, etc. (Nikles, 2007). The initial installation also requires proper calibration with respect to some reference temperature. For the current

paper, temperature data were recorded with a device offering a temperature resolution of 0.05°C, a spatial resolution of 1 m and a range of 5 km.

A water leakage across the dike generates a thermal anomaly recordable by the fiber optic. Several measurements over time allow following the temporal evolution of this anomaly. The acquired raw temperature data can thus be formulated as spatio-temporal data. However, the identification of leakage signatures on the raw temperature data is not easy due to the influence of several environmental factors. Consequently, subsequent processing of these data is required in order to extract useful information concerning the leakages.

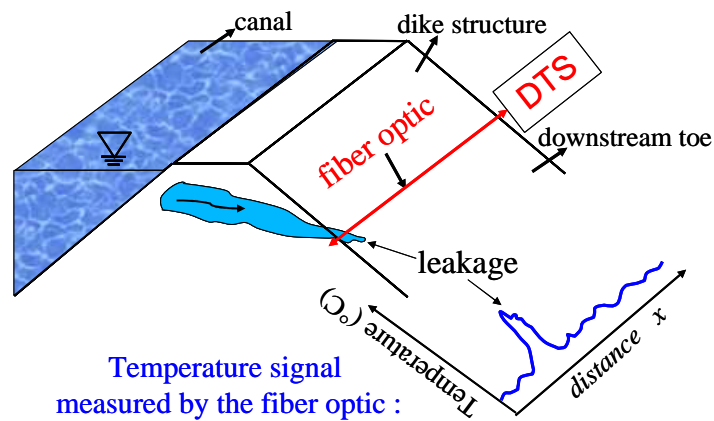


Figure 1 : Schematic of thermal dike monitoring for leakage detection using distributed fiber optic sensors.

The data recorded by the fiber optic can be written as a two-dimensional signal, a function of time t and distance x : $\mathbf{Y} = \{y(t, x), | 1 \leq t \leq N_t, 1 \leq x \leq N_x\}$, where N_x and N_t represent the fiber length and the total number of acquisitions, respectively. In principal, significant flow of water due to leakages could be identified by measuring the difference of temperature between that of the canal and the soil in which fiber is buried. However, this difference could equally be a result of other factors like existing structures (drains, tunnels, and manholes), seasonal temperature variations, solar radiation, precipitations, soil heterogeneities, etc. Moreover, the acquired signal is strongly influenced by response of the near surface in which fiber is buried, masking the leakage related useful information. Anomaly detection, particularly the leakage detection requires isolation of all these factors from the raw temperature data.

The recorded signal can be modeled as a mixture of above factors. Even though, these factors can be a non-linear function of temperature, the temperature values induced by these factors are considered without trying to quantify the factors which produced these values. A source as function of distance along the fiber is attributed to different factors allowing to express the recorded temperature as a weighted linear mixture of these factors. In addition, considering the physical independence of these factors, the associated temperature sources can be assumed independent. The temperature matrix can thus be expressed as:

$$\mathbf{Y} = \mathbf{M}\mathbf{F} + \mathbf{B} \quad (1)$$

where, $\mathbf{M} \in \mathfrak{R}^{N_t \times p}$ represents the mixing matrix, $\mathbf{F} \in \mathfrak{R}^{p \times N_x}$ the independent sources induced by the factors, and $\mathbf{B} \in \mathfrak{R}^{N_t \times N_x}$ the noise.

Different pre-processing techniques such as data deseasoning and normalization could be employed for attenuating the influence of certain factors. Likewise, the temporal periods of precipitations must be identified as they could introduce false alarms in the detection algorithms. In this regard, a criterion for identifying such periods, based on higher order statistics, was proposed (Khan *et al.*, 2008b).

Leakage Detection Methodologies

Two methodologies based on advanced signal processing techniques were developed by the authors (Khan *et al.*, 2008a and Khan *et al.*, 2010). A brief review of these methodologies would be presented in this section.

Medium Term Analysis : Source Separation Approach

The fiber optic allows monitoring of temperature profiles along the dike with metric resolution. An approach based on the separation of different thermal contributions (sources) could be used. The idea would be to find the matrices \mathbf{M} and \mathbf{F} in Eq. (1) given only the observation matrix \mathbf{Y} , the recorded temperature data. The most commonly used techniques for source separation are singular value decomposition (SVD) (Klema *et al.*, 1980) and independent component analysis (ICA) (Hyvärinen *et al.*, 2000).

In the first step, SVD, a matrix filtering technique, allows decomposition of original data space into orthogonal subspaces. The output of SVD is then treated using the independent component analysis, based on the assumption that the sources are mutually independent. The goal is to estimate the sources and their contributions to the mixture by maximizing a criterion of statistical independence. The algorithmic details do not fit into the scope of this paper and the interested readers can refer to (Hyvärinen, 2000). The final output is a leakage detection parameter, $\mathbf{Y}_{leakage}$, a function of distance and time. The algorithm is summarized by the schematic of Figure 2.

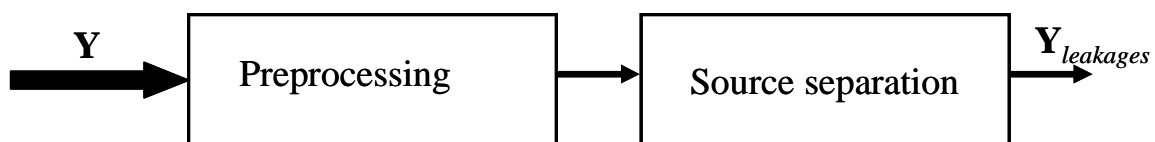


Figure 2 : Source separation based approach for leakage detection.

Daily Analysis : Dissimilarity Based Approach

The source separation approach is useful for the case of monitoring. However, for real time early warning system, another approach was proposed by authors (Khan *et al.*, 2010). The method is based on the assumption that singularities such as leakages, existing structures, ground singularities, etc., show daily temperature variations that are different from the non-singular zones. The main hypothesis is that a large part of the dike is constituted of non-singularity zones and the method would be applicable to the sites satisfying this condition.

The different stages of the proposed technique are summarized in Figure 3. The system analyzes data for a given day k at all the sensing distances. The meteorological conditions are first verified to ensure precipitation free days. A reference vector representing the 24-hour temperature variation for non-singular zones is estimated from the data itself.

The deviation with respect to this reference allows formulating a measure of dissimilarity with the help of L_2 norm. The resultant dissimilarity measure, $d_k(x)$, is a function of distance. A thresholding scheme based on probabilistic modeling of this measure and a constant false alarm rate is then applied. This formulation allows to obtain an adaptable threshold for each analysis day with a fixed probability of false alarm. The output is thus a detector of singularities as a function of distance along the fiber for each day. Subsequent adaptation of the system can allow the sub-daily analysis as well. The proposed detection system has the capability to serve as an *early warning system*, identifying the anomalies well before they are observable through visual inspections.

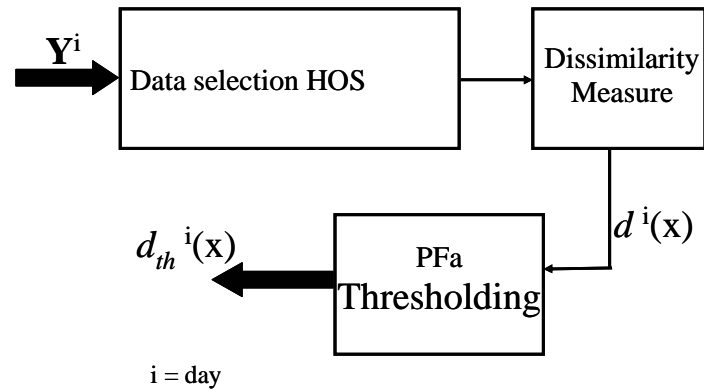


Figure 3 : Daily alarm system based approach for leakage detection.

Results and Discussion

Over the last 10 years, EDF has developed expertise from optical fiber sensor installation to data interpretation for structural health monitoring of dikes. The application of the leakage detection methodologies on the real temperature data acquired at two experimental sites of EDF would be presented in this paper.

Experimental Site # 1

The first experimental site is located in the south of France with a Mediterranean climate. The fiber optic cable is buried at the downstream toe of the dike; bordering the feed canal at a depth of 1 m. Figure 4 shows the installation configuration, where 2.2 km of fiber circumvents two drains, D1 and D2. The geological conditions at the site imply that the fiber is at two different elevation levels. The raw temperature data shown in Figure 5 as a spatio-temporal function depict seasonal temperature variations and the two drains.

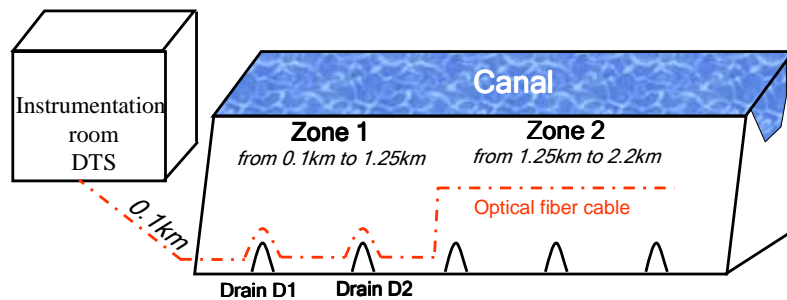


Figure 4 : Illustration of fiber optic installation at experimental site # 1.

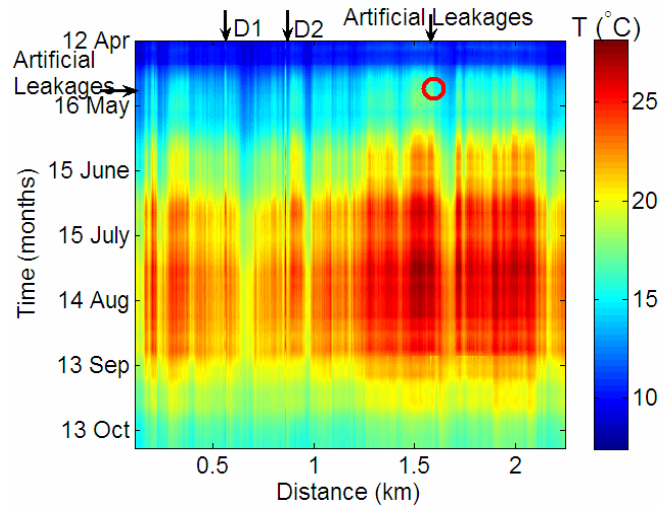


Figure 5 : Raw temperature data acquired at experimental site # 1 over 2 kms and 6-months in 2005.

In order to test the leakage detection system, artificial percolation type leakages were used at this site, their generation not fitting into the scope of this paper. These leakages, controlled in terms of their flow rate, localization and duration, are described in Table 1.

Table 1. Structures and artificial leakages at experimental site # 1.

	Drains		Leakages			Hot Point
	D1	D2	L1	L2	L3	HP
Distance (km)	0.561	0.858	1.566	1.551	1.573	0.674
Time (May)	-	-	10 (afternoon)	12 (afternoon)	12 (eve)	10 (morning)
Flow rate (l/min)	-	-	5	1	1	-

In the first instance, the source separation approach results would be presented. The preprocessing consists of normalization and precipitation identification using the higher order statistics criterion. The output of the detection scheme, $\mathbf{Y}_{leakage}$, is shown in Figure 6. A zoom in the vicinity of the artificial leakages, L1, L2 and L3, shows an efficient detection and localization of the artificial leakages. The temporal evolution of these leakages can also be followed with this result. L1 is detected as being the most energetic, followed by L2, whereas L3 is detected with the least energy due to its low flow rate as well as its initiation during the night when the water and air temperature difference is not significant. In order to localize the leakages, the result can be projected on the distance axis, $y_{proj}(x)$. One such projection during october, 2005 (Figure 7) allows detection of real leakages, localized over several meters, just before and after the second drain, D2. The periodic analysis done for the data acquired in october 2007 for the same site allowed detection of these real leakages as well.

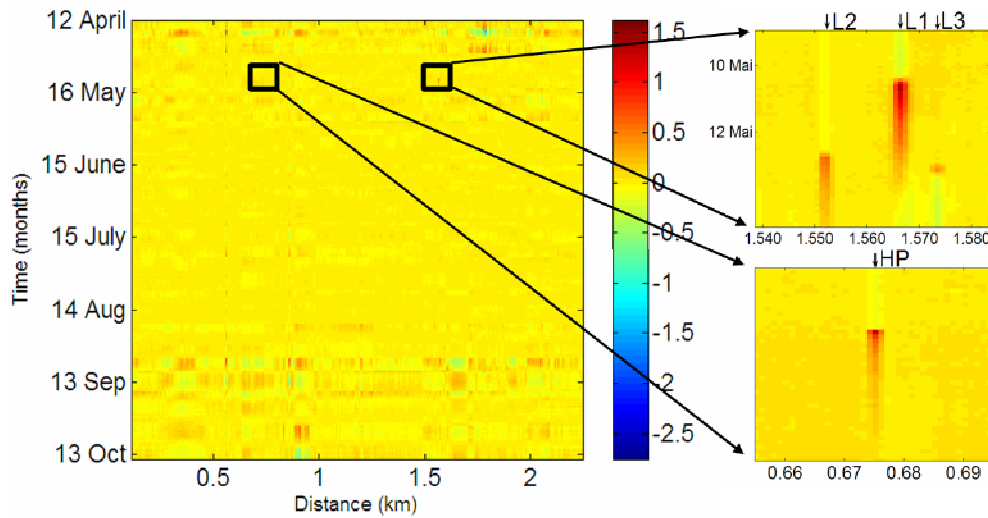


Figure 6 : Source separation based detection results for experimental site # 1 for year 2005.

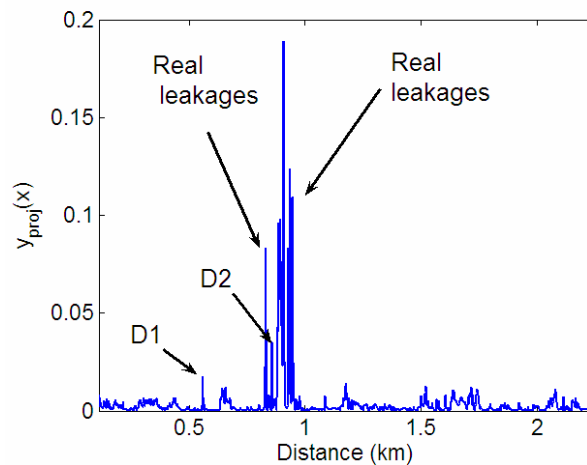


Figure 7 : Projection of source separation based detection results for experimental site # 1 with real leakages in October, 2005.

The daily analysis approach also allows the detection of the artificial as well the real leakages. The results on the artificial and real leakages of 2005 are not presented here in order to avoid repetition. However, in order to highlight the significance of daily alarm system, the detection results for 7 days in the year 2007 are shown in Figure 8, whereby the drains and the real leakages are identified as anomalies. The detection parameter was normalized here with respect to the maximum for each day. This kind of graphic can be very useful to follow the evolution of different anomalies.

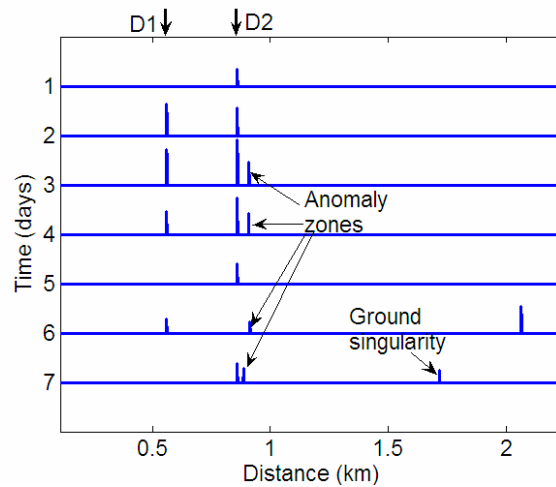


Figure 8 : Detection results for daily alarm based analysis system for experimental site # 1 over 7 days in 2007.

Experimental Site # 2

The second experimental site considered here 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. Periodic visual inspections have shown the presence of leakages over a large part of the dike. The detection results using the source separation approach are shown in Figure 9 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 with the visual inspection results. Moreover, 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 9a) disappear in july (Figure 9b). This is a peculiarity of the site, where the main canal exhibits lots of seasonal variations in terms of its flow rate, resulting in the fact that certain leakages appear and disappear over the course of time.

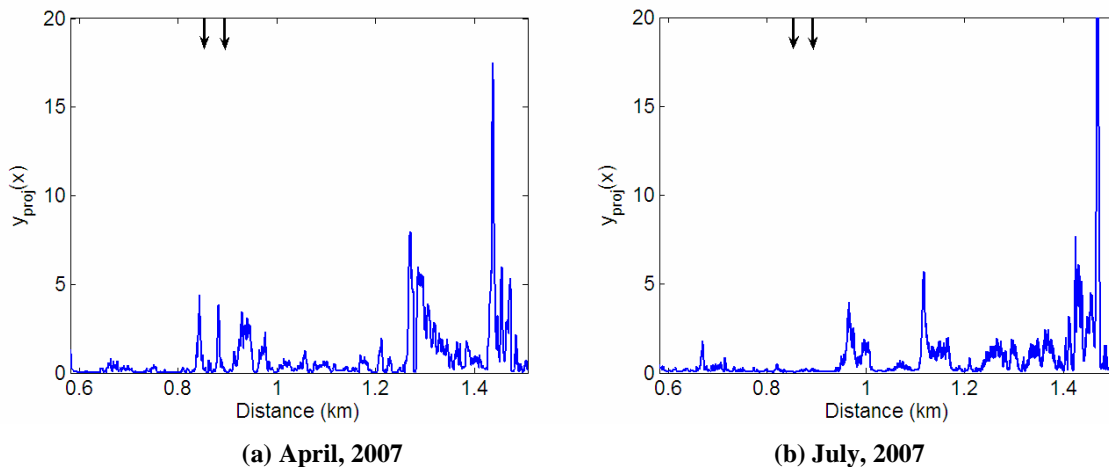


Figure 9 : Projection of source separation based detection results for experimental site # 2.

Conclusion

Health monitoring of dams and dikes is primordial in order to avoid the failure of these structures. Internal erosion, being a major cause of ruptures in dams and dikes, alters the temperature field of the structure. The fiber optic based distributed temperature sensors provide a semi-autonomous surveillance solution, monitoring while ensuring quasi-visual inspection along the entire dike length. The raw temperature data acquired through these sensors must be analyzed for identification of leakage related information. Two signal processing based approaches, a medium term approach and a daily alert system based approach, were shown to be very efficient in detection of leakages. The proposed methods were validated on two different sites of EDF, equipped with fiber optic temperature sensors along the dike, whereby real leakages were detected. The distributed fiber optic temperature sensor based detection is an *early warning system* owing to the fact that it is automatic and allows measuring the anomalies well before they are physically visible.

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