



On Earth Dam Leak Detection Based on Using Fiber-Optic Distributed Temperature Sensor (Case Study: Canal Embankment on the Rhône River, France)

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Abstract. The main aim of this paper is to detect and fully evaluate the leakage potential of an embankment based on the fiber-optic distributed temperature sensing (DTS) under an R&D program in France between Cementys, INRAE and CNR (Compagnie Nationale du Rhône). The field experimental works and real data measurements have been applied for the current study. The developed measurement and monitoring system in this study which installed inside of the embankment has consisted of distributed fiber optic sensors, PT100 sensors, TDR sensors, Vibrating wire sensors, and Meteorological sensors. The solar-based energy resource has been connected to the developed measurement system and WIFI technology has been used for data transferring. The achieved result of heat measurement shows that the current study developed system is able to measure the inside embankment temperature with the perfect accuracy instantaneously. The achieved results allow us to monitor the real-time temperature difference in the main body of the embankment. Seasonal evaluation of results shows that the higher potential of leakage is occurred during winter and in the deeper parts throughout the embankment. Besides, generating an exact Equi-potential dispersion map with considerable accuracy compare with previous research and relationships has been performed. The comparison results of current study measurement and previous research on the IRFTA analytical model shows that the foundation level of the embankment has a high potential location for leakage.

Keywords: Embankment · Earth dam · Leakage · Distributed temperature sensing · Fiber optic · Heat transfer · Internal erosion

1 Introduction

Nowadays, there are different types of embankment health monitoring systems which help to increase the durability of the infrastructure such as the embankment dam within

operation time. Recent research has addressed that both physical and environmental assessments are necessary to consider the infrastructure's health monitoring and reliability (Abbasimaedeh et al. 2017). The control of infrastructure foundation's settlement, dynamic behavior, crack and damage propagation, using non-destructive tests, and corrosion and erosion measurements are suggested as the most considerable methods to health monitoring of infrastructures (Abbasimaedeh et al. 2018). The Seepage study with an emphasis on the heat measurement in hydraulic structures as a new interdisciplinary research topic for erosion potential estimating and monitoring has recently been taken into consideration for researchers (Johansson 1991; Armbruster and Merkler 1982; Armbruster et al. 1989).

There are various methods of seepage assessment such as field laboratory tests, geophysical tests, telecommunication tests, and heat transport analysis (Abbasimaedeh et al. 2020). However, the temperature data has been expressed as a feasible method, able to give real information on seepage condition. The coupled modeling are normally used to assess the seepage and thermal change in the soil media with an emphasis on the validation of temperature measurement. However, it is possible to monitor the seepage potential considering the fluid velocity, while the method is rarely used.

Several numbers of studies have been conducted on thermal and seepage transportation in the soil media from 1960 to 1980 (Stallman 1965; Birman 1968; Cartwright 1968, 1974; Sorey 1971; Domenico and Palciauskas 1973; Smith and Chapman 1983). The result of the mentioned studies indicates that heat transportation by water movement has considerable effects on the variation of temperature gradients within the earth (Bredenhoeft and Papadopulos 1965). Moreover, it is depicted that the temperature of seepage flows can play the role of natural leakage tracer which applied to the hydraulic structures (Dornstadter and Heinemann 2013). In recent decades, considerable developments have applied to the heat transportation method with the support of advanced technology in temperature measurement as well as the development of analytic approaches. In general, using temperature to estimate seepage in embankments was divided into two categories, active and passive, including analytical and numerical approaches with an emphasis on the physical parameters.

The analytical methods have highly been counseled for the localized leakage potential. The proper approach is not only able to prospect a very small leakage process but also can qualitatively specify the intensity of seepage inside the embankment (Beck et al. 2010a, b, Khan et al. 2014, 2008, Lang et al. 2008, Pyayt et al. 2013, Radzicki and Bonelli 2010b). Previous scientific assessments show that the model with physical parameters can be used to quantitatively evaluate the seepage velocity considering temperature data. The Lag-time and amplitude proposed methods by Johansson could be a considerable approach for the preliminary seepage analysis of simple geometry and saturated soil layers (Johansson 1997).

On the other hand, the numerical simulation is a strongly accurate solution in case of complicated geometry of the embankment. Numerical modeling with the proper application of boundary and initial conditions brings out the way to compute seepage velocity

in the embankment using temperature monitoring. As a model verification, the vast number of thermal-hydraulic parameters will be considered for exact computing the concurrent temperature and seepage potential in the embankment. Then the expected temperatures from numerical solutions will be compared with temperature measurements to find out the closest result from which seepage velocity (Bui et al. 1968; Bui et al. 2018, 2016; Johansson 1997; Radzicki and Bonelli 2010a, 2012, Yousefi et al. 2013; Shija and MacQuarrie 2015; Smith and Konrad 2008; Velasquez 2007).

Today, the developed thermometric methods based on the fiber optic temperature sensors are considered as the most promising method to detect the leakage area in earth dams (Artieres 2012). The distributed optical fiber allows the detection of the early signs of internal leakage and erosion all along the embankment (Johansson 1997; Perzlmaier 2007; Côté et al. 1991). This method called first time so-called “passive” method which has been developed and consists to measure the natural temperature along a horizontal optical fiber located in the saturated area (Johansson 1997, 2005). Another measurement technic is called “active” which has been developed in order to quantify locally the identified anomaly (Aufleger et al. 1998). It consists of artificially heating the soil near the optical fiber and to estimate the heat quantity carries away with the flow, which is directly correlated to the water flow rate (Artières et al. 2007; Zhou and Zhao 2018).

In this paper, the result of a filed experimental work using Cementys patented developed instruments to measure the heating transfer in the main body of the embankment using the DTS method has been recorded, analyzed, and compared with the suggested method by the previous researcher. As the case study, the measurements were performed on a real embankment located on the Rhone river in France. Cementys pieces of equipment and its high-quality QA/QC and observation methods have been used for the installation of instruments and fiber optics. The main aim of the current study is to consider the efficiency of the innovative methods and instruments of measurement to measure the internal heat transfer compare with previous approved analytical methods. The current study’s development In measurement technics will help us to monitor the real-time inside temperature everywhere of the embankment during the operation time. Furthermore, the proposed method helps to find the exact value and location of the leakage potential in the main body of the embankment. Finally, the lower cost range of the maintenance, choosing the best method to control the leakage, higher range of safety factor, and real-time health monitoring with an emphasis on erosion and leakage damages in embankment structures will be achieved using the current paper method.

2 Materials and Methods

Conceptual Methods and Assumption

To measure the leakage potential and erosion steps in the main body of the embankment the heat transport evaluation with an emphasis on the collaborated real scale field experimental work has been performed with Cementys and CNR on the embankment located on the Rhône river. The heat transport in the body of the hydraulic structures is described by an energy relationship (Eq. 1) in the literature. The second and the third terms of this equation correlated the conductive and advective heat transport processes respectively, where the advective process is defined as the transport of heat with the

mass of flowing water. In this relation T is the temperature ($^{\circ}\text{C}$), C is the volumetric heat capacity of the porous domain, C_f is the volumetric heat capacity of water and λ is the thermal conductivity of the porous domain (Radzicki and Bonelli 2012).

$$C \frac{\partial T}{\partial t} - \lambda \frac{\delta T}{\delta x^2} - v C_f \frac{\partial T}{\partial x^2} = 0 \quad (1)$$

The major dependencies were described by the energy conservation equation. Considering the zero water flow velocity, there is only heat conduction, which is a relatively slow process. However, even a change in the moisture content of the soil medium is able for the significantly affect local thermal front velocities. While the fluid motion (seepage, leakage), heat is also allowed to transport along with the water mass. This process is called advection and generates a much more substantial heat flow which is faster the fluid flow. In addition, to get an exact expression of temperature loadings on boundary conditions (reservoir, air temperature), temperature sensors are often required to be set up in damming structure (Radzicki and Bonelli 2012).

Temperatures of the air and the water in the reservoir are the principal thermal loadings for the dam. In addition, It is assumed that other heat sources like geothermal and frozen processes, radiation, and wind influence are neglected. In the case of the null water velocity, there is only conductive, slow heat transport from the dam surfaces inward the dam. Hence with rising the water velocity, the temperature from the reservoir is moved quicker with the mass of water which results in the temperature field perturbation. Similarly, there are significant temperature differences in the embankment body, especially between the high and low potential of seepage. Finally, an analysis of the temperature distribution in the dam's body allows for leakage identification. Such temperature measurements can be realized with the fiber optic cable at every meter of the embankment's length. This technology called distributed temperature sensing (DTS) gives a possibility of continuous monitoring of the structure in space.

Case Study

Within the scope of an R&D program in the collaboration with Cementys (an international science-based company to monitor, implement, examine, and optimize the maintenance of various projects, infrastructures, constructions) and CNR (Compagnie Nationale du Rhône) aiming to produce tools and monitoring methods for the leak detection inside the earth dams, a sensitive section of an embankment has been instrumented with optical fibers to complete the old configuration in the place monitoring system.

The structure instrumented is a canal embankment of a hydroelectric scheme owned by the CNR on the Rhone river in France (Fig. 1). Rhone has about 812 (km) length which expanded between Switzerland and France. In terms of flow, of all the rivers flowing in the Mediterranean, the Rhône is second after the Nile, if one does not take into account the Black Sea, where the Danube and the Don flow in particular.

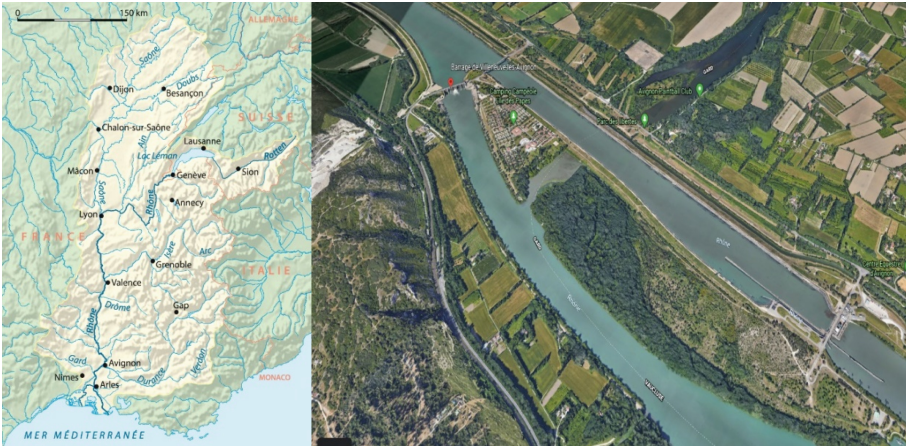


Fig. 1. The geological map of the Rhone river (left) and the aerial photo of embankment location (right).

Instrument Installation

An overview of the current study's DTS system is shown in Fig. 2. The new monitoring installed the system on the embankment is consisted of a THMLoggerData Logger, and a SensoLogger optical fiber interrogator. The main energy for the measurement system has been supported by the solar-powered (Fig. 3). Furthermore, the system is continuously connected to the web-based THM Insight® software, providing a real-time display of the data in the control center.

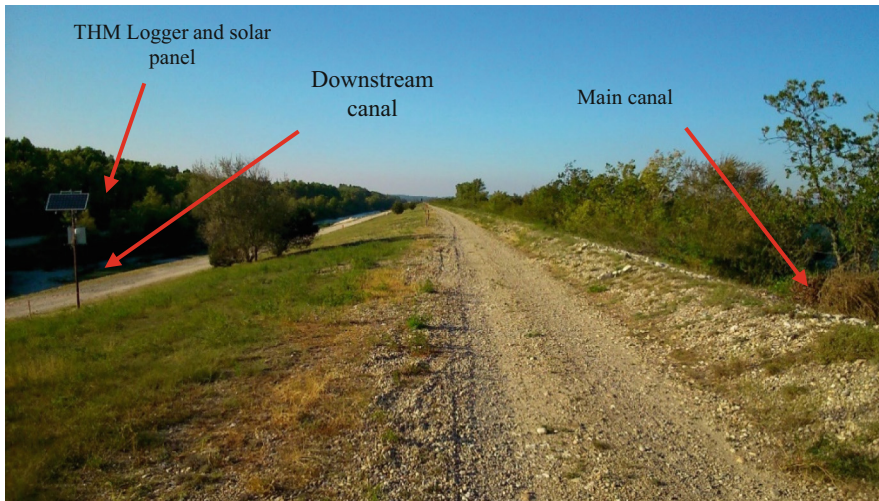


Fig. 2. Canal embankment of a hydroelectric scheme owned by the CNR (Compagnie Nationale du Rhône) over the Rhone river with installed instruments for heat measurement.

The monitoring and measurement system used in the current study includes the following instruments:

- Distributed fiber optic which has been supported by the following sensors:

- SensoLux Detect®: Distributed temperature sensors (Raman backscatter) with Sixteen numbers of 12 m depth thermometric tubes are installed in the leakage potential area. However, two sensors with similar lengths have been installed in safe and lower leakage potential areas of the embankment. All these tubes instrumented with a SensoLux Detect optical fiber cable. The achieved data by mentioned optical fiber are able to become a database to produce the 2D dispersion map of the temperature in the leakage potential areas. Furthermore, in order to localize the leakage areas with the longitudinal profile of the temperature, another optical fiber cable has been installed in the 50 cm depth of the soil in the downstream toe.

- SensoLux TM®: Distributed strain measurement (Brillouin backscatter) at the top of the embankment to observe the settlement of the ground (Fig. 4).



Fig. 3. THM logger on the downside of the embankment (left) solar system and metrological sensor (right)

- PT100 sensors: temperature measurement in the thermometric tubes in order to correct and calibrate the optical fiber measurements.
- TDR sensors: water content measurement in the soil around the leakage area to control the leakage evolution.
- Vibrating wire interstitial pressure cells water level measurements in order to feed the statistical analysis.

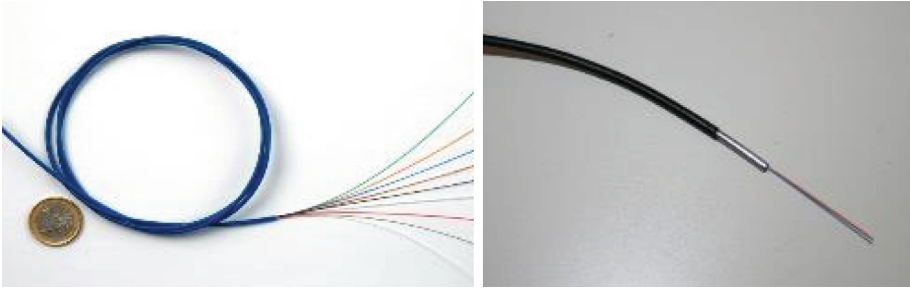


Fig. 4. SensoLux TM cables (left) and SensoLux Detect (right)

- Meteorological sensors: environmental parameters measurements (atmospheric pressure, air temperature wind speed, humidity, rainfall) in order to the feed the statistical analysis (Fig. 5).



Fig. 5. PT100 sensors, TDR sensors, Vibrating wire sensors and Meteorological sensors (left to right)

Temperature measurements have been performed continuously without heating the soil “passive method”. During punctual campaigns (twice a year), the soil was heated around the fiber “active method” in the downstream toe. This measurement helps us to better identification of the leakage area considering the increase of the thermal contrast between areas in which only the conduction phenomenon occurs and areas in which both conduction and advection phenomena occur. Moreover, the mentioned measurement will enable us to highlight the evolution of the flow rate, without giving it a precise value. The fiber optic and THM Logger installation location on the embankment have been depicted in the Fig. 6. It is depicted that the reference tubes are located in both side of the embankment which has a lower potential of the leakage while to aim of a perfect measurement other tubes are considered on the middle part of the embankment with the higher range of leakage potential.

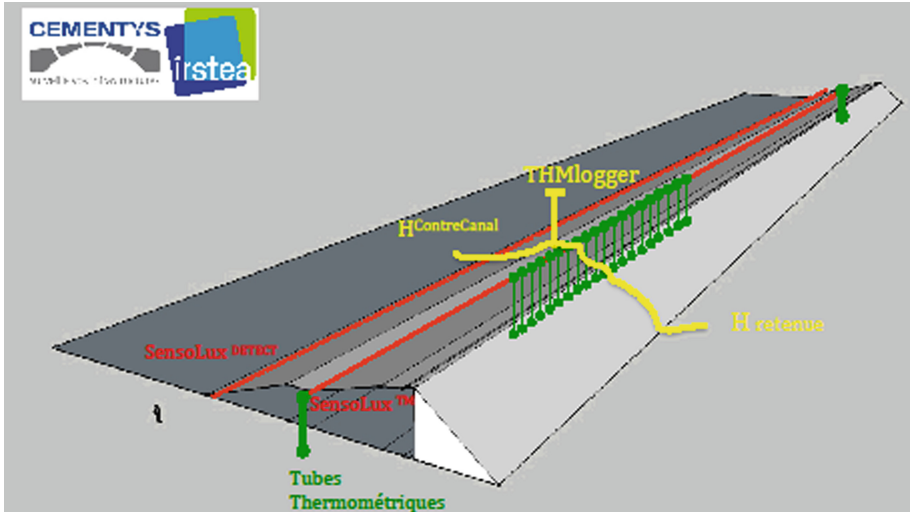


Fig. 6. Schematic of sensors implantation throughout the embankment

3 Results and Discussion

After installation of all optical fibers and connecting to the available old measurement instruments, the system been fully checked under a professional QA/QC program by Cementys professional, and then all the equipment and sensors were fully calibrated by some sample tests. The achieved data relating to the temperature profile in vertical pipes are illustrated in Fig. 7. The result shows that the average air temperature during winter (January) has been detected approximately 5 °C while the average soil temperature at depth in the foundation observed approximately 13 °C (left side). Within the summer (July) the average air temperature is detected around 25 °C and the mean of the soil temperature at depth in the foundation was measured around 11 °C (right side). In a deep and accurate assessment, it is observed that the weather's temperature has a significant effect on the soil temperature up to 3 m in depth (zone A). The small seepage flow has no remarkable effect on the seasonal temperature variation in the embankment and is constant to approximately 3 m depth.

The exact penetration depth is related to soil mechanical and chemical properties. The achieved result shows that the temperature profile will be changed in accordance with the effect of the rate of heat transportation and the concentrated seepage flow. In this case, the temperature profile is no longer constant in-depth. A good example is zone C which indicates the leakage area of the embankment. This is illustrated in Fig. 8 where the seepage flow in the foundation has been detected (depth greater than 10 m, Zone C). This Figure illustrates the leakage detection between first to mid of the March (every 2 h). Furthermore, the heat transported has a considerable correspondence to the water temperature of the reservoir in previous weeks before the current measurement.

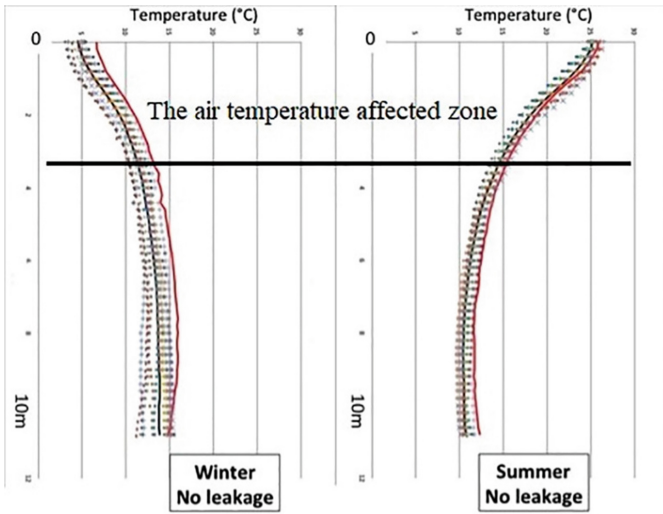


Fig. 7. Vertical temperature measurement in vertical borehole (pipes) during summer and winter

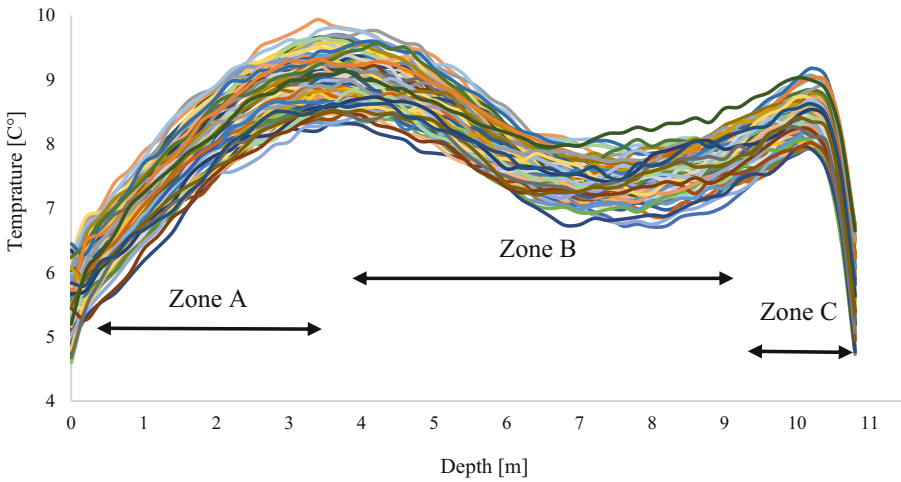


Fig. 8. Vertical temperature measurement in vertical pipes of leakage potential area

A three-month length of temperature variation record between January and February 2015 on the downstream toe of the embankment as the sample is depicted in Fig. 9. Total 2 years temperature record has been performed in this study. All the temperature values have been recorded with an emphasis on the depth, length, and exact time of detection.

The mentioned data can generate a strong database of heat transportation differences and enough useful to accurately estimate the seasonal leakage potential in the embankment. Such fiber optics' data have been used to produce the accurate dispersion real-time map of leakage and interior temperature of the embankment. Results of such measurement show that there is a leakage area in the length of 650 to 750 m of fiber optic.

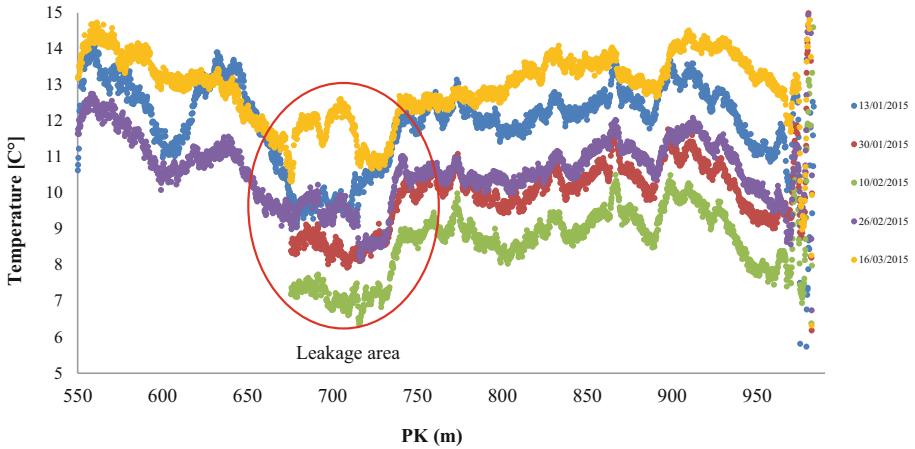


Fig. 9. Horizontal temperature measurement throughout the embankment in the foundation level

Based on the achieved data and performing an accurate statistical analysis the innovated leakage monitoring system has been developed in the scheme of a live 2D Equi-potential (Equivalent dispersion) dispersion map of the temperature inside the embankment to estimate the leakage potential. The developed Equi-potential dispersion map represents the difference between the temperature profiles in the tubes in the leakage area and the temperature profiles of the two available reference tubes located far away from the leakage area. Hence, the obtained contrasts enable to detect the leakage area, which is colder in-depth than the available tubes. As an example, a framed photo of the Equi-potential dispersion map which has been obtained in winter is illustrated. The result shows that the water temperature is significantly colder than the soil at this depth. This 2D Equi-potential dispersion map enables to display in real-time on the web application THM Insight (Fig. 10).

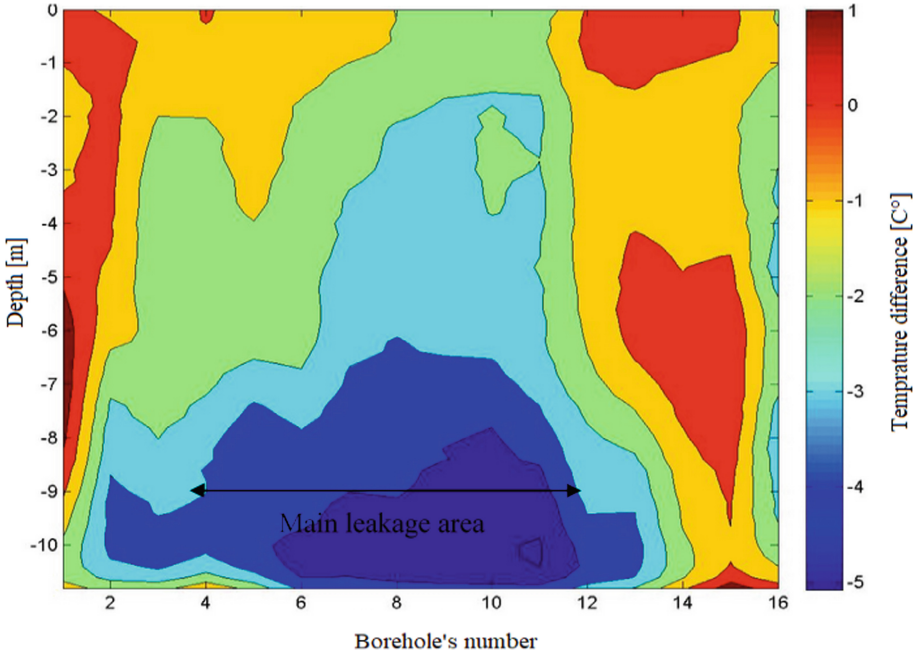


Fig. 10. Equi-potential dispersion map of the difference between the temperature profiles in the tubes and the reference temperature profiles.

To make validation in the comparison with the results of previous methods, the IRFTA model for velocity analysis (Radzicki and Bonelli 2010, 2012) on the current study's data was performed. The mentioned method is an application to the thermal phenomena of the original IRFA model (Bonelli 2009). The model is based on the influence of air temperature and water temperature on the measured temperature in the embankment and its foundation. Furthermore, the method allows us to quantify the delay time, the thermal diffusivity of the soil, and the Peclet number, which is the ratio of the quantity of heat transported by the water and the quantity of diffusion heat. After that, the method allows us to estimate the magnitude of the water velocity, which is illustrated in Fig. 11 during leakage potential. Results show that the higher range of water velocity has been detected in the deeper part of the embankment. Furthermore, it shows the current work have an acceptable ability to accurate leakage location.

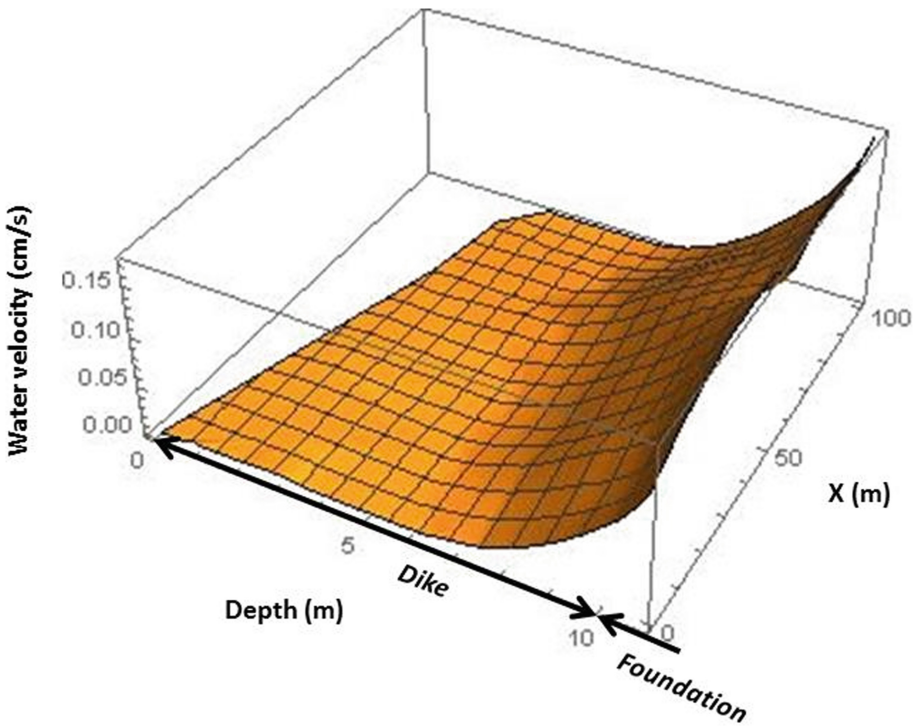


Fig. 11. The water velocity values based on the IRFTA model.

4 Conclusions

This paper introduced a developed practical method to measure and estimate the leakage potential using a real-time monitoring system based on the distributed temperature sensor (DTS). The health monitoring system is installed in a sensitive leakage area (internal erosion) of an embankment located on the Rhone river in France. The specificity of the proposed system is that the optical fibers were installed both vertically and horizontally in the main body of the embankment and downstream toe. The measured temperature received by the vertical measurement using fiber optics in eighteen tubes distributed along the embankment is the main database for future analysis in this system. The proposed pattern allowed us to plot a two-dimensional Equi-potential dispersion map of the dam temperature which is displayed in real-time on a web interface. Achieved results show that the current paper's developed method to measure the inside heat transportation of the embankments has enough accuracy in a comparison with previous research and analytical methods. Besides, the proposed measurement technology can estimate the exact leakage potential location as a live dispersion map in the embankment during operation time. Considering the advantages of our real-time monitoring system which addressed in the introduction part, the owner selected the economic method (diaphragm wall) to control the seepage and leakage in the embankment which considerably had the

optimum cost for its organization and was successful to fully control the leakage and eventually inside erosion.

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