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Thermal Seepage Monitoring in the Earth Dams with Impulse Response Function Analysis Model

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Abstract

In the paper we present the Impulse Response Function Thermal Analysis (IRFTA) model and its application to leakage detection by analysis of temperature measured in the body of earth dam or dike of the canals. This method bases on theory of Green's function that is applied to coupled heat and water transport description. Direct leakage flow or even only variation of humidity of the soil due to seepage presence, influence on heat transport in the soil. In consequence IRFTA model application for the parametrical description of heat transport, allows for analysis of water transport in dike or dam. In consequence we can identify leakages but also we can analyse even small seepage changes and estimate intensity of this process. It is possible due to fact that IRFTA model is not only statistical model but its parameters have physical definition. Application of IRFTA model is predicted for the distributed fiber optic temperature measurements, especially for a sensor installed in the downstream toe of the earth hydraulic structure, close to the upstream face. By this way a system of thermal monitoring continuing along the dam can be installed with small cost and with minimal earth works on already existing structure.

Introduction

Nowadays one of the most effective and promising method which is used for leakages identification on the dams and dikes is the thermal analysis method [2]-[7].

Heat transport in the body of the earth hydraulic structure is described by energy Equation (1). The second and the third term of this equation describe respectively the conductive and advective heat transport processes, where advective process is defined as the transport of heat with the mass of flowing water.

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

where: T - temperature
C - volumetric heat capacity of porous domain
C_f - volumetric heat capacity of water
λ - thermal conductivity of porous domain

Temperatures of the air and the water in the reservoir are the principal thermal loadings for the dam, supposing that other heat sources like geothermal and frozen processes, radiation and wind influence are neglected. For the null water velocity there is only conductive, slow heat transport from the dam surfaces inward the dam. With rising of the water velocity, temperature from the reservoir is moved quicker with the error masse of water. It results in the temperature field perturbation. Similarly, there are also thermal significant differences in the dike's body temperature between the zones of low and of faster seepage. Finally, an analysis of the temperature distribution in the dam's body allows for leakage identification. Moreover, temperature measurements can be realized with the fiber optic cable at every meter of its length [1],[2],[4]. In consequence, this technology called distributed temperature sensing (DTS) gives a possibility of continuous monitoring of the structure in space.

However, a correct analysis of the measured temperature is possible only with application of the suitable heat transport models. Particularly, it refers to temperature measurements performed in the downstream toe of dam, which zone is very attractive for dams thermal leakage monitoring. Firstly, in the most cases leakage path that cross the body of dam comes to this zone. Secondly, installation of the fiber optic cable in this zone is cheap and easy and can be realized on the existing dams. Nevertheless, a model to be applied to analyze thermal data from the downstream toe of dam musts take into consideration both external thermal loadings (air temperature or/and water temperature) as well the soil saturation degrees changes. To date, there are two advanced and robust methods that allows for analysis of the temperature measurements from the downstream toe of dam, the Impulse Response Function Thermal Analysis (IRFTA) model [2], [4] and the Source Separation Technique for Processing of Thermometric Data From Fiber-Optic DTS [6]. The first, IRFTA model allows for physical parameters identification of heat and water transport in the dams including leakage identification and its intensity estimation. However, it needs for analysis minimum

of two months temperature series. This model is very effective for physical analysis of leakage and erosion processes. The second methods of the Source Separation Technique uses signal analysis methods being fully statistical model. It allows for very fast leakage detection [7]. However, it not allows for estimation of physical parameters of the processes.
Finally, with these two models it is possible nowadays a complex and very precise dam's thermal monitoring with fiber optics that is localised at whichever point of the dams, particularly in its downstream toe.
In its paper we present IRFTA model and methodology of its application. After theoretical background, two earth hydraulic structures thermal analysis is described, the first experimental basin in Aix-en-Provence and the second dike of canal Oraison.

Background of IRFTA model

Energy Equation (1) describes a parabolic-linear problem. It means that heat transport (diffusional-advective) can be assumed to behave in the linear manner if the thermal porous medium properties and the water velocity are constant.
In consequence we can use the Green's function methodology to build an suitable model of the relevant problem. Using this approach the loading (input signal) $a(t)$ and the system's response (output signal) $y(t)$ are connected by the impulse response function of the system $h(t)$ as follows:

$$y(t) = (h * a)(t) = \int_0^t h(t-\tau)\, a(\tau)\, d\tau \qquad (2)$$

where * is the mathematical convolution operator.
In other words, impulse response function describes how input signal (in form of Dirac delta) is modified by the porous zone of the dam. In our model we used an approximation of the impulse response function in the form of the two-parameters (α,η) exponential decay:

$$h(t) \approx R(\alpha,\eta) \qquad (3)$$

The role of the parameters is explained by harmonic analysis. Under slowly varying loading conditions, η representing time-lag which quantifies the time elapsing between the onset of the loading and the response of the system in the point of measurements and α is the is the signal damping factor.
Finally the IRFTA model has the following form :

$$T(x,t) = \theta_C + R_w(x,t) * \theta_w(x) + R_{air}(x,t) * \theta_{air}(x) \qquad (4)$$

where: θ_C - constant

R_w, R_{air} – impulse response function approximation respectively for the water temperature and the air temperature loadings

θ_w, θ_{air} – water temperature and air temperature loadings on dam surface

Measured temperature $T(x,t)$ is formed by superposition of responses of dam for the water temperature and the air temperature loadings, that are represented respectively in the second and the third term of Equation (4). Finally the IRFTA model has four parameters. Two of them α_w and η_w inform about transformation of the thermal signal from the upstream face (water temperature loading). Downstream thermal signal (air temperature loading) modification is described by next two parameters α_{air} and η_{air}.
In particular conditions, IRFTA model can be applied in reduced form. If temperature sensor is located directly in the saturated zone of seepage and the air temperature influence is neglected we can use the following model :

$$T(x,t) = \theta_C + h_w(x,t) * \theta_w(x) \qquad (5)$$

Contrary, if there is non water temperature influence on the fiber optics temperature, it is possible to use model :

$$T(x,t) = \theta_C + h_{air}(x,t) * \theta_{air}(x) \qquad (6)$$

Analysis of experimental basin dike temperature with 2-parameter IRFTA model

Description of the site
An IRFA model was used to analyze the data measured at the Aix-en-Provence experimental basin. This rectangular four dikes hydraulic work was specially constructed to test a system of the fiber optics thermal surveillance. The dam was build using clayey material with the permeability at saturation of 10^{-11} ms^{-1}. In the some chosen locations of the corps, there were localized highly permeable sand zones closed in the geotextile envelopes to create the artificial leakages. They were installed in high or low position and they can be treated as suffusion zones, compared their fable permeability with the permeability of the corps clay. Leakage discharges were controlled by the valves. Downstream face of the dam was covered by the geotextile having cables of the fiber optic which were installed at three different levels, the top one (T-OF), the middle one (M-OF) and the bottom one (B-OF) (Figure 3). There were directed contact between the geotextile layer and the downstream outflow of the artificial leakage zones. Geotextile with the fiber optics were retained by a refill. To reduce of the description volume, in this article we present only the most interested results of the analysis obtained for the west dike of the basin where are both high and low position leakages (Figure 1 and 2).

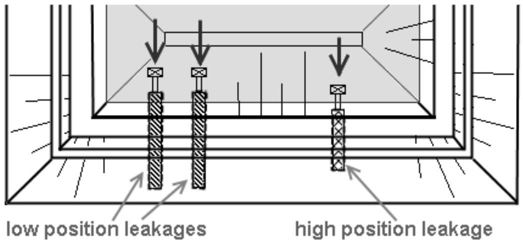

Figure 1: View of the west dike of experimental basin with location of the leakages [2]

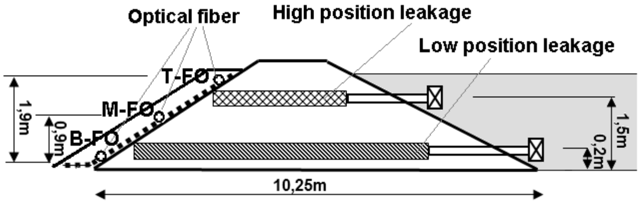

Figure 2: Sectional view of the dike of basin with location of the leakages [2]

Preliminary analysis

First analysis of data with both air temperature and water temperature influence models (Equation (4)) showed that influence of the water temperature on the temperatures measured with fiber optic is neglected. In such case application of two-parameter models (one loading influence) in place of four-parameter model (air temperature and water temperature influence), reduces time of the computation and increase of data reproduction accuracy. In consequence we used for Aix-en-Provence basin analysis only air temperature influence model defined with Equation (6).

Firstly, the analysis of temperature from the all fiber optics were made in the function of temperature of air and in the second step in the function of temperature measured by the thermal sensor installed some centimetres below the crest of dike. In both cases the leakages zones could not be cleared identified. However, in the second case, we found that the values of the coefficient of the determination are higher values, what signifies that model better reproduce the data. Its means that for this hydraulic work, influence of the external influences thermal charges other than only air temperature is important, for example the influence of the solar radiation or the wind. The temperature measured by the thermal sensor below the crest includes all this external additional thermal influence and its application gives immediately better results in the analysis. Though, it wasn't sufficient to clearly identify the leakages.

Leakage detection analysis

In fact, it was highly suspected that there is a strong locally variation of the external thermal charge along the dike. To take it into consideration we made the analyze of series of temperature measured every meter by fiber optics cables B-FO and M-OF in the function of the temperatures measured in the respective points (in the same cross section of the dike) by the cable T-FO. This approach gave excellent results which are presented at the Figure 3, where cross marks and triangle marks signify respectively the results obtained for B-FO and M-FO cables.

On the western side of dike of the basin, there are three artificial leakages zones, two in the low position and one in the high position (Figure 1 and 2). We see clearly the zones of all three leakages for FO-B cable there where η parameter has significantly lower values and in increasing of *1-R2* function values. FO-B cable is located below all leakages and it detects them all. M-FO cable is situated only below high position leakage and only this leakage influences significantly the values of η parameters and *1-R2* function. This notice is important for optimal fiber optics cable location in land-side (downstream) toe of the dike and dams.

On the other side, in the case of Aix-en-Provence experimental basin the values of the parameter α are almost stable what characterize the zones of soil out of directed seepage velocity influence. The variation of this parameter strongly depends on the contact direct between the thermal sensor and the current of water. Formulation of this problem is beyond the scope of this paper.

To the contrary, η values parameters depend on not only direct water flow influence but on ground saturation level as well. For discussed basin, we found that the water discharge was finally weak and all water flow was diffused in the bottom part of the geotextile close to the ground. Finally it did not touch directly the fiber optic which was installed on the geotextile. It explains why there was non water temperature influence on soil temperature measurements.

However, even if there is no direct influence of the water on the fiber optic temperature, changes in humidity of soil and of geotextile due to the leakage presence results in the changes of locale values of the thermal conductivity and thermal capacity. In consequence, the conductive heat transport from the downstream face of the dike is different between the zones with and without the leakage. It is registered in the parameter η values variation.

On the other side, we said that impulse response analysis model describes only linear relation in the heat transfer. Nevertheless, there were significant variations of the artificial leakages discharges, in the basin in Aix-en-Provence. They were linked with the not constant position of the reservoir level. It results in the nonlinear perturbation in heat transport due to the humidity variation in function of time around the leakage zone. In consequence, the IRFTA model was not capable to reproduce perfectly the data from the fiber optic which have been measured close to the leakage. This nonlinear effect linked only with seepage presence also helps us to confirm the leakage zone presence by the lower values of the coefficient of determination R2. On the Figure 3 in the place of R2 we used the function 1-R2 so the leakages are visible in this function values increase.

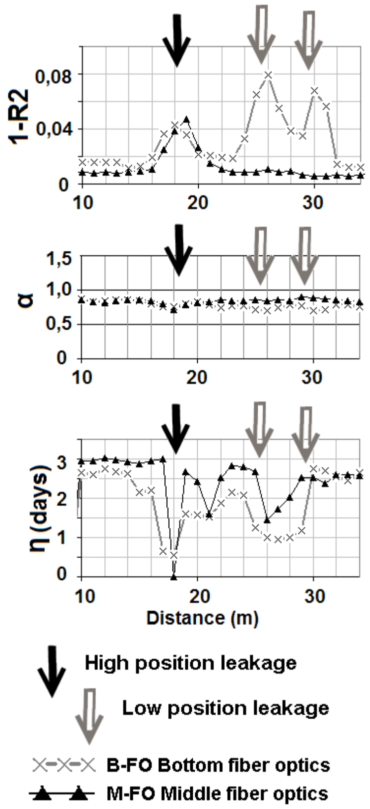

Figure 3: Results of the IRFTA analysis for the west dike temperature measurements of the Aix-en-Provence basin

However, even with these non-linear effects reproduction of data by the model is excellent. Coefficient of determination is always higher than 0,92 even for the zone of the leakage (for the function 1-R2 consequently is lower than 0,08). Examples of the model values and measured temperatures values are presented at the Figure 4 for the zone with and without the leakage.

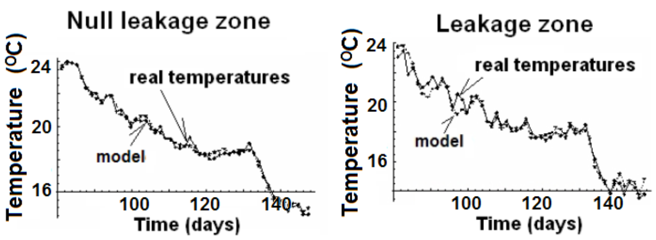

Figure 4: Examples of the reproduction by the IRFTA model the temperatures measured in the zones with and without the leakage.

Analysis of dike's canal temperature with 4-parameters IRFTA model

Description of the site

Second application of the IRFTA model described in this paper focuses on thermal analysis of seepage process in about 27 metres height dike of the Oraison canal. Cross-section of this canal is presented at Figure 5. Bottom and slopes of the canal are covered by protection elements made from reinforced concrete slabs being simultaneously an impermeable layer. Fiber optic cable is situated at the land-side toe of the dike at the distance of 1000m. Next, it changes its location over a few tens of meters increasing at the top of the berm (Figure 6). For its entire length it is located at the depth of 0,8m below the soil surface.

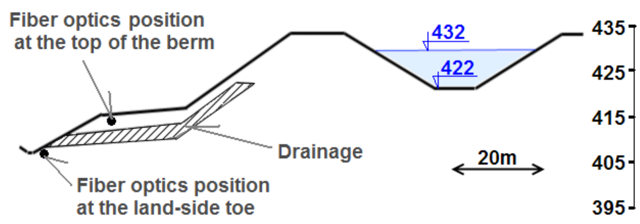

Figure 5: Cross-section of Oraison canal

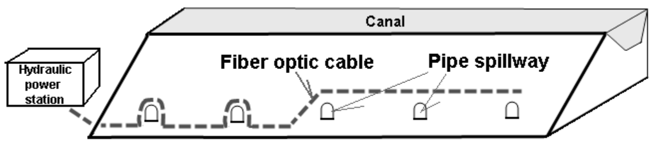

Figure 6: Schema of fiber optic monitoring system

Results of the analysis

Preliminary analysis showed that temperatures at the most part of the measurement points is influenced significantly by both air and water temperature. In consequence, a full 4-parameter IRFTA model defined with Equation (4) has been applied for modelisation. Reproduction of the data by model was excellent. For all measurements points a coefficient of determination R2 was higher then 0,99 (for the values of function 1-R2 consequently is lower than 0,01). Analysis of the IRFTA model parameters values and their variations allowed to identify several hydro-thermal zones of the dike in relation to different seepage intensity. Due to limit place in the article we describe only three, chosen zones. First zone is localized between 700 and 815 m of the fiber optic cable. Results of the analysis for this zone are presented at the Figure 7. For the air temperature influence on the fiber optic temperature, we observe that values of α_{air} parameter varies from 0,8 to 0,7. It means respectively only from 20% to 30% signal damping and in consequence significant influence of the air temperature. Time-lag of the response of the fiber temperature for the air temperature loading (η_{air}) was about 20 to 30 days. At the Figure 8 we see that time-lag between the maximal temperatures or the minimal temperatures for the curves of the air temperature and of the fiber optic temperature has similar value. It confirms a correct calculation of parameters values by IRFTA model.

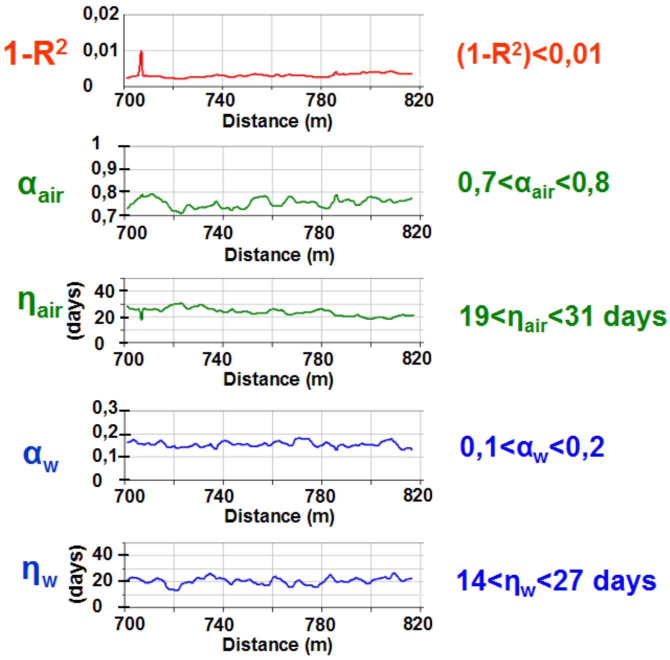

Figure 7: Values of the IRFTA models parameters for temperature analysis between 700 and 815m distance of the fiber optic cable

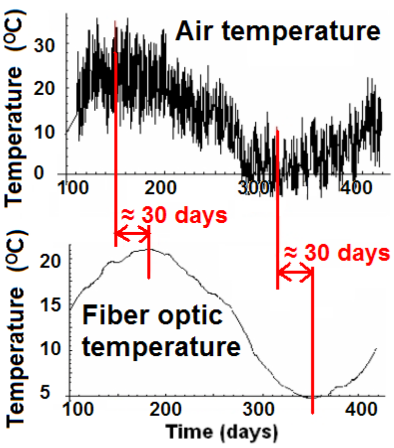

Figure 8: Time-lag of the response of the fiber optic temperature for air temperature influence

On the other side, influence of the water temperature is very low. Damping of the water temperature signal equals from 80% to 90% (α_w varies from 0,2 to 0,1) and the time of the response (η_w) is from 14 to 27 days. These values of IRFTA models parameters exclude important seepage process in this zone of dike.

The second presented zone is localized on the distance from 880 m to 950 m of the fiber optic. Results of the modelisation are presented at the Figure 9. Comparing the values of the parameters between previous zone and this one we see that for signal transformation of the water temperature influence, damping is little lower particularly for the distance from 880m to 925m where α_w equals from 0,2 to 0,25 (damping varies from 80% to 75%). Simultaneously transport of the heat is faster for the water temperature signal. η_w varies between 9 and 20 days. Simultaneously, also the air temperature signal transport is stronger (α_{air} equals from 0,76 to 0,91) and faster (η_{air} equals from 11 to 20 days) than as the case of the previous zone. These changes in air temperature signal transformation parameters have clear physical explication. Due to more significant seepage process, humidity zone around the seepage zone is larger and degree of saturation of the soil in this zone is higher. It results in changes in values of thermal parameters of porous medium as volumetric heat capacity and thermal conductivity.

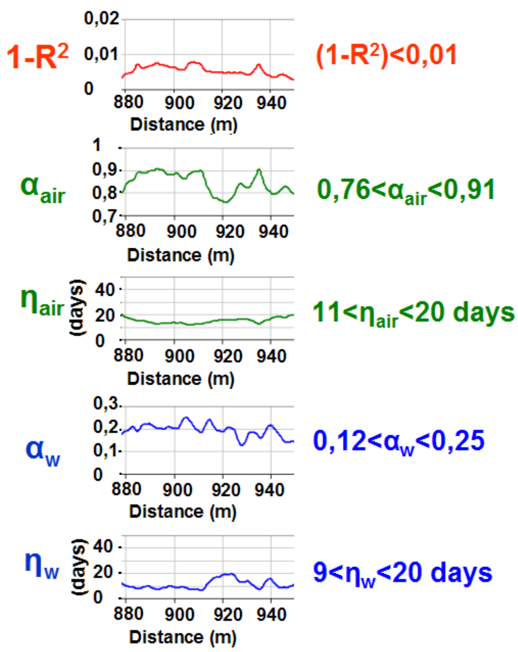

Figure 9: Values of IRFTA models parameters for temperature analysis between 880 and 950m distance of the fiber optic cable

Finally it causes acceleration of conductive heat transport process, which is stronger and faster, also from land-side of the dike (air temperature influence) inward the dam. However, even in spite of the fact of more significant seepage presence in the discussed zone, values of the IRFTA model parameters exclude existence of the leakage problem.

In the third presented zone fiber optic cable (from 990 to 1100 m) is situated close to the crest of the berm. In consequence, this cable is outside of seepage influence. We observe only significant air temperature influence (α_{air} varies from 0,8 to 0,96). For water temperature influence, α_w values are closed to 0 and time-lag η_w seeks to very large values of some thousands days. Physically it means a null water temperature influence. In some singular points because of convergence difficulty in real data reproduction these values are different. However α_w even there is lower then 0,1.

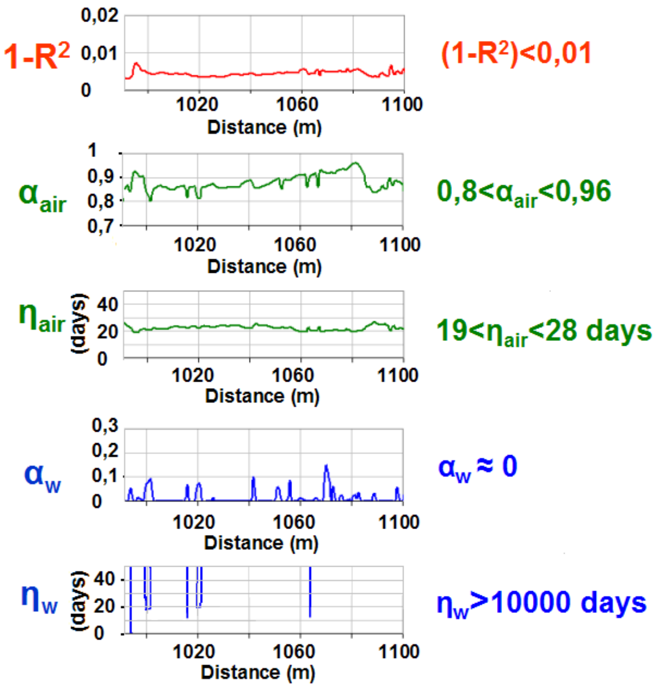

Figure 10: Values of IRFTA models parameters for temperature analysis between 990 and 1100 m distance of the fiber optic cable

Using IRFTA model we identified also a location of the spillways of the canals. They were constructed as the concrete, open pipes that cross the dike from canal-side to land-side. Usually, their inlet is above the normal water level. They work exceptionally only in flood time when the water level in canal rises significantly. During the temperature measurements the pipes were empty and filled only by air. To be installed in continuous length in the dike the fiber optic cable was situated around and close to these spillways. In the places of spillways location the values of the models parameters show clearly only air temperature influence ($\alpha_{air} \approx$ 0,95; $\alpha_w \approx 0$). Owing to the concrete frame of the spillways, transport of the heat from air is faster ($\eta_w \approx 8$ days) there than in the other zones of the dikes where the fiber optic cable was surrounded only by the soil.

Conclusion

In the paper we showed the application of IRFTA model to the thermal analysis of hydraulic field of the two different earth hydraulic structures. We see that with this method, very small seepage process influence related only to degree of humidity variation as well a seepage that touches directly the fiber optic cable, both can be easy detected. Moreover, physical definition of the model parameters allows for estimation of the seepage filtration intensity. Analysis of the model's parameters values and their variation gives also a possibility of clear physical interpretation of the observed thermal-hydraulic processes, not possible to be performed with only statistical models. It is particularly important for the earth dams and dikes of the canals behaviors assessments.

In consequence, thermal monitoring and analysis of temperature with IRFTA model increase of hydraulic structure security level. It minimizes also the cost of eventual reparation work of the dam due to fact that erosion process (linked with leakage process) is early and precisely defined.

IRFTA model application is particularly predicted for analysis of the temperature measured with fiber optic cable. This technology allows for continuous monitoring of the leakages process along the dike. Installation of the fiber optics cable in the downstream (land-side) toe of earth dam or dike is easy and cheap and can be recommended as efficient monitoring system of existing structures.

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