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Impulse Response Function Analysis model application to the thermal seepage monitoring in the earth dams

K. RADZICKI^a, S. BONELLI^b

a. Cracow University of Technology, ul. Warszawska 24, 31155 CRACOW

b. Cemagref, 3275 Route de Cezanne CS 40061 Cedex 5, 13182 AIX-EN-PROVENCE

Résumé :

L'érosion interne, liée avec la présence de fuites, est un danger bien connu pour la sécurité des barrages en terre et des digues. Actuellement, l'analyse thermométrique du remblais d'un ouvrage hydraulique est considérée comme la méthode la plus efficace et prometteuse pour identifier ces processus. Le papier présente une méthode appelée Analyse Thermique de la Fonction de Réponse Impulsionnelle (IRFTA) ainsi qu'un exemple de son application à l'analyse des mesures de température réalisés dans un barrage en terre. Le modèle IRFTA permet de décrire précisément le couplage transport de l'eau et de la chaleur dans le corps du barrage et en conséquence, il permet d'identifier des fuites mêmes minimales ainsi que leur variation.

Abstract :

Internal erosion, linked with the leakage presence, is a well known menace for the dams and the dikes safety. Nowadays one of the most effective and promising method which is used to identify this process is the thermic analysis of the hydraulic body. In the paper we present a method called Impulse Response Function Thermic Analysis (IRFTA) and its application to earths dams monitoring. IRFTA model allows precisely describe the coupled heat and water transport in dams body and in consequence recognizing even minimal seepage appearance and changing. Application of IRFTA model to analyze the temperature measurements realized for an earth dam is presented in the article.

Mots clefs : barrage en terre, fuite, surveillance thermique, reponse impulsionnelle

1 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 [1],[3],[6]. 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.

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

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 [2]. 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 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],[3],[5],[6]. 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 must take into consideration both external thermal loadings (air temperature or/and water temperature) as well the soil saturation degrees changes.

In this paper we present Impulse Response Function Thermal Analysis (IRFTA) model [1], [3], [4] that allows for physical parameters identification of heat and water transport in the dams including leakage identification and its intensity estimation. This model is specially predicted to be used for analysis of the temperature data measured inside of the downstream toe of earth dam. After theoretical background, IRFTA model application results for dike of canal Oraison are described.

2 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 a 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:

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

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.

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

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 signal damping factor.

Finally the IRFTA model has the following form :

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

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 :

$$T(x, t) = \theta_c + h_w(x, t) * \theta_w(t) \quad (5)$$

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

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

3 Analysis of dike's canal temperature with IRFTA model

3.1 Description of the site

An example of the 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 1. 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 2). For its entire length it is located at the depth of 0,8m below the soil surface.

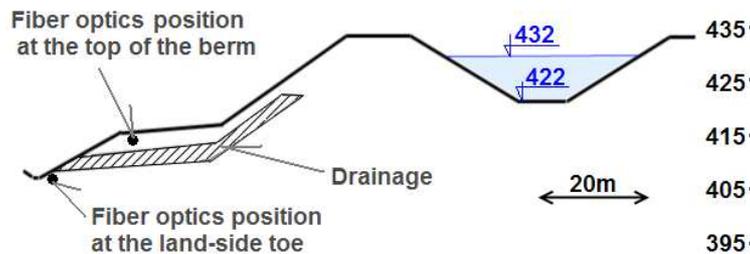


FIG. 1 – Cross-section of Oraison canal.

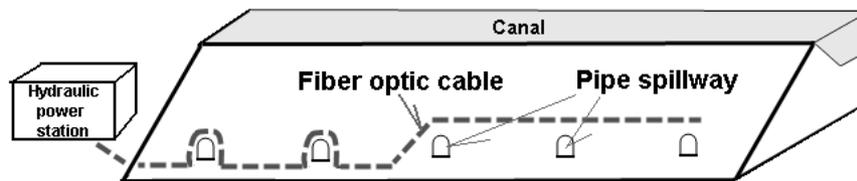


FIG. 2– Schema of fiber optic monitoring system.

3.2 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 R^2 was higher than 0,99 (for the values of function 1- R^2 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 3. 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. Calculated time-lag of the response of the fiber temperature for the air temperature loading (η_{air}) was about 20 to 30 days. In the Figure 4 we see that time-lag between the air temperature maximum value and the fiber optic temperature maximum value is similar. The same we observe for the minimum values. This confirms a correct estimation of time-lag values by IRFTA model.

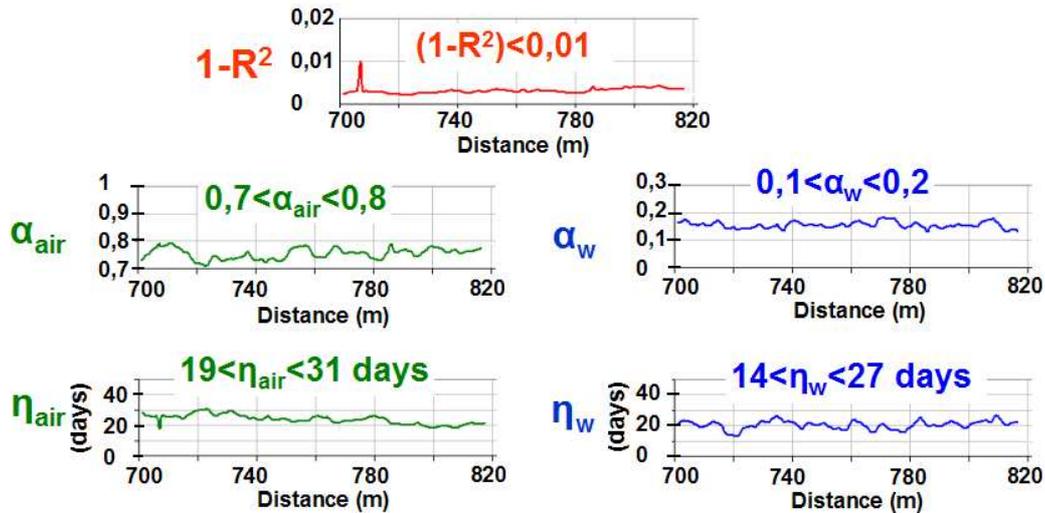


FIG. 3 – Values of the IRFTA models parameters for temperature analysis between 700 and 815m distance of the fiber optic cable.

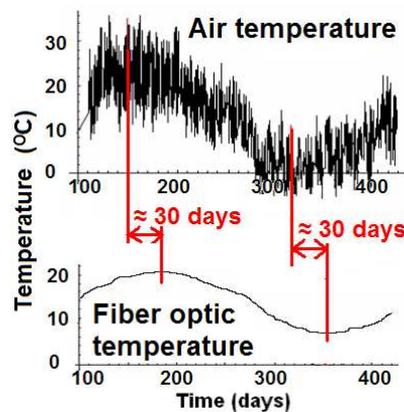


FIG. 4 – Time-lag of the response of the fiber optic temperature for air temperature influence.

On the other side, the influence of water temperature is very weak. Damping of water temperature signal equals from 80% to 90% (α_w varies from 0,2 to 0,1) and the time of response (η_w) is from 14 to 27 days. These values of IRFTA models parameters exclude important seepage process in this zone of the 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 5. 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. 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.

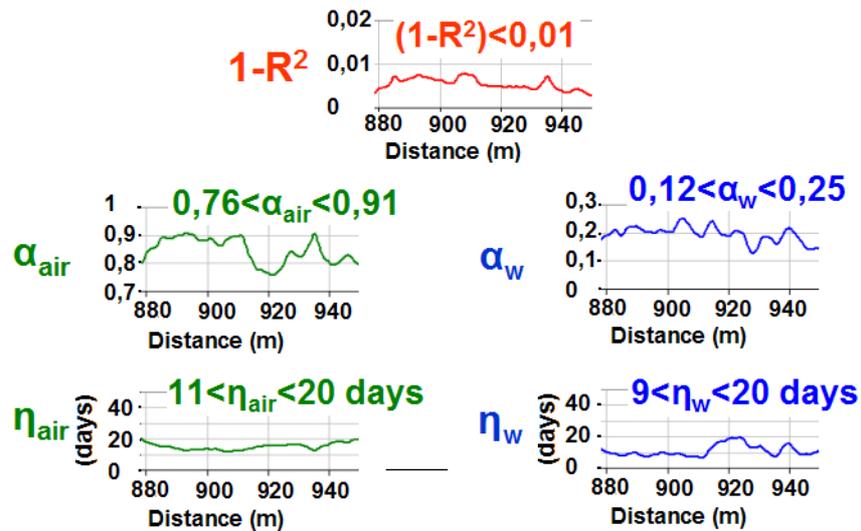


FIG. 5 – Values of IRFTA models parameters for temperature analysis between 880 and 950m distance of the fiber optic cable.

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. Results of the analysis for this zone are presented at the Figure 6. 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 than 0,1.

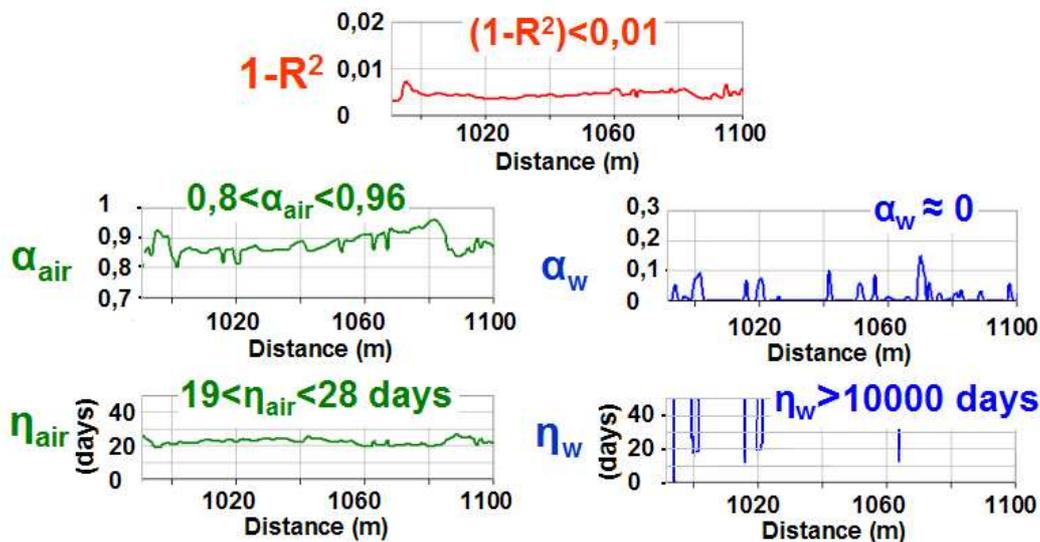


FIG. 6 – Values of IRFTA models parameters for temperature analysis between 990 and 1100 m distance of the fiber optic cable.

4 Conclusion

In the paper we showed the application of IRFTA model to the thermal analysis of hydraulic field of the dike of the canal. We see that with this method, very small seepage process influence related only to degree of humidity variation can be easily 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 behaviours 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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