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K. Radzicky, Stéphane Bonelli

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Krzysztof RADZICKI[1], Stéphane BONELLI[2]

[1]Cracow University of Technology

Ul. Warszawska 24, 31155 Kraków, Poland: - e-mail : radzicki@hotmail.fr

[2]IRSTEA (previously Cemagref)
3275 Route de Cezanne, CS 40061, 13182 Aix-en-Provence Cedex 5, France: - e-mail : stephane.bonelli@cemagref.fr

Analysis of the distributed temperature measurements taken on fibre optic cable installed in the body of earth dams is nowadays the most efficient tool of leakage identification and of seepage processes monitoring. However, it requires application of advanced models describing relations between heat and water transport. The IRFTA (impulse response function thermal analysis) model developed by the Authors is one of these models. The model parameters have physical definition. Application of the IRFTA model to the analyse temperature values measured at existing dams has proved its usability in identifying leakages in the early development phase thereof, while precisely determining the intensity of the filtration process by parametric physical description, and also analysing its time-variability.
This paper presents numerical modelling of coupled heat and water transport for selected case of developing suffusion process in a 15 m height homogenous earth dam, as well as the results of thermal analysis of this process by the IRFTA model. The analysis was performed with regard to different lengths of the suffusion layer, various values of the suffusion layer hydraulic conductivity, and various locations of the temperature sensors in the downstream toe of the dam. The study proved correct the IRFTA model being capable to provide for determination of the changes occurring in the filtration intensity. Yet, definition of the opportunity to apply this model to carrying out direct assessment of the suffusion process will require the further study, and that depends on, inter alia, the location of the suffusion layer, as well as the location of the measuring point.

Key words
Dam, leakage, suffusion, monitoring, impulse response function, IRFTA model, fibre optic, distributed temperature sensing, data analysis, heat and water transport.

I INTRODUCTION

Thermal monitoring is nowadays one of the most promising tools of the leakage detection and analysis. This method bases on relations in the coupled heat and water transport. Changes in the soil moisture content of the body of the earth hydraulic structure or in velocity of water flowing through it result in disturbances of its temperature field.

The temperature values of both the air and the water in 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 [Johansson, 1997]. For the null water velocity, there is only conductive, slow heat transport from the dam surfaces inward the dam. With rising of water velocity, temperature is quicker transferred from the reservoir with water mass. It results in temperature field perturbation. Similarly, there are also significant thermal differences in the dike's body temperature between the zones of both the low and the faster seepages.

There are several methods of temperature measurements analysis, among which the models of temperature series data analysis play the most important role [Beck et all, 2010; Radzicki, 2011]. One of them is IRFTA (impulse response function thermal analysis) model developed by the Authors [Radzicki 2009; Radzicki, Bonelli, 2010]. Physical definition of model parameters and a possibility to analyse temperature measurements affected by both the ambient air and the reservoir water temperature values are the important model abilities. The analysis can be performed for temperature measurements carried out in any part of the dam, including also in its unsaturated part. Application of the IRFTA model to analyse temperature values measured in existing dams has proved its usability to identify leakages in their early development phase, precise determining the intensity of the filtration process by parametric physical description, and also to analyse its time-variability [Radzicki, Bonelli, 2010].

Currently, the studies are carried out being aimed at definition of the opportunity to determine the development characteristics of the suffusion process through modelling temperature measurements in the dam body with application of the IRFTA model. This paper presents a selected example of the IRFTA model application to analyse the filtration field in the aspect of analysing a developing suffusion process in a 15 m high homogenous dam. The suffusion process development scenario assumed that suffusion process had developed in the saturation zone above the dam downstream toe. Numerical modelling was performed over the dam and the coupled heat and water transport taking place within it. Modelling exercises were carried out taking into account two different lengths of the suffusion layer and two various values of the hydraulic conductivity of the suffusion layer. This paper specifically describes the influence of suffusion layer development on temperature change in the downstream toe of the dam. This zone provides for cost-effective installation of fibre optic distributed temperature sensing cable at existing dams. Consequently, the analysis of the opportunity to modelling temperature measurements taken in this zone appears particularly interesting.

The subsequent sections of this paper present the general description of numerical modelling processes and the direct analysis thereof, the background of the IRFTA model, as well as the application results of this model.

II NUMERICAL MODELLING

The aim of the modelling exercises performed was to compare the changes in thermal-hydraulic field of the cross-section of a 15 m high homogenous earth dam for various lengths of the suffusion layer and various values of the hydraulic conductivity in the suffusion layer. The dam was modelled by finite element method with use of the Feflow software. Three following cases were considered: the first involving a suffusion-free dam, the second - for the suffusion layer stretching between the dam downstream slope and the dam axis, and the third one - i.e. when the suffusion layer runs throughout the dam cross-section. Geometric dimensions of the suffusion layer are assumed as the time-constant for each of the modelling exercises. Also, identical initial and boundary conditions were applied in each of them. That provided for comparison of thermal-hydraulic fields for various cases of the suffusion layer length.

Constant, 12 m high, water-table level was assumed. The real air and water temperature values were assumed, as measured with 15 minute interval on one of dams in Poland. The influence of other external thermal loads was passed over in numerical modelling. The total modelling time covered 4 years.

The soil hydraulic conductivity in the dam cross-section beyond the suffusion layer was assumed as 1e-5 ms^{-1}, and that of the ground-base as 1e-10 ms^{-1}. The suffusion layer was modelled exclusively through reduction of the hydraulic conductivity value in relation to other part of the dam body. The soil hydraulic conductivity in the suffusion layer was assumed as 1e-4 ms^{-1}, or 1e-3 ms^{-1}. Simplified, rectangular geometry of the suffusion layer and 1 m high suffusion layer were assumed. The lower edge of the suffusion layer is situated at 5 m altitude of the dam height.

III DIRECT ANALYSIS OF THE THERMAL-HYDRAULIC FIELD

The suffusion layer developing within the dam influences essentially the filtration field, thus consequently affecting heat distribution processes. The influence of the suffusion process on thermal-hydraulic field varies depending on, amongst others, the dam design solution, the scale of this structure, the ratio of the suffusion layer length and the length of the structure cross-section, and on the value of the soil hydraulic conductivity within the suffusion layer and beyond it.

In case when the suffusion layer is lacking in the homogenous dam described, heat is transported primarily from the upper part of the upstream slope jointly with water, diagonally downwards, towards the downstream toe, in accordance with the highest values of both the hydraulic gradient and the directions of the filtration vectors. Figure 2A presents an example of isothermal distribution for the case in question, including the direction of the thermal front, as marked with white arrows.

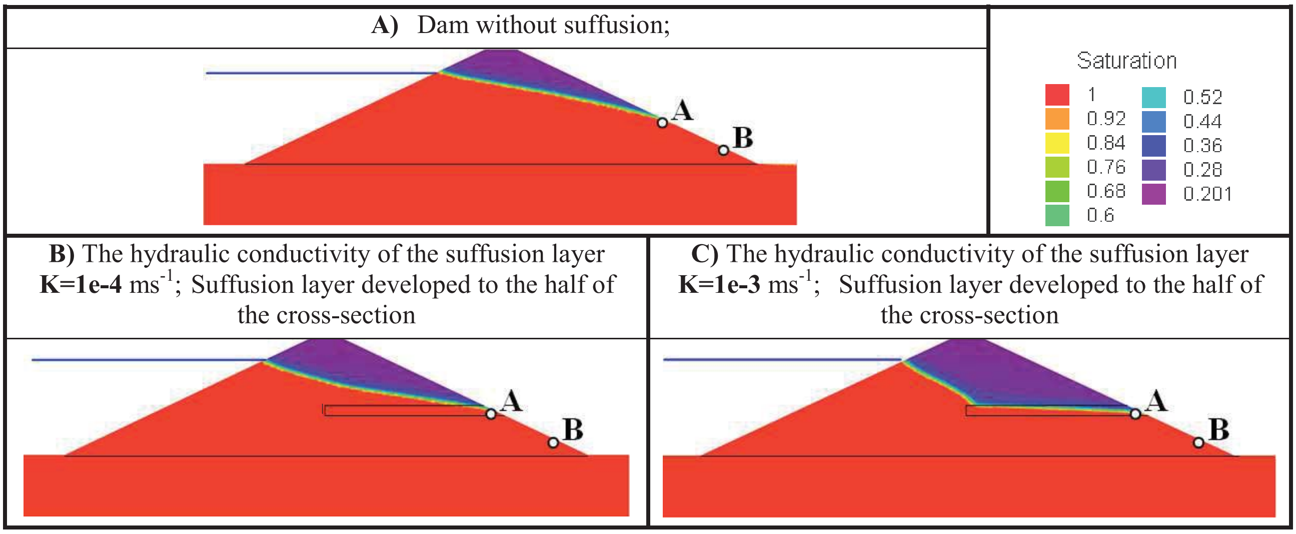

Figure 1: Saturation curve for different lengths of suffusion layer and for different values of suffusion layer hydraulic conductivity

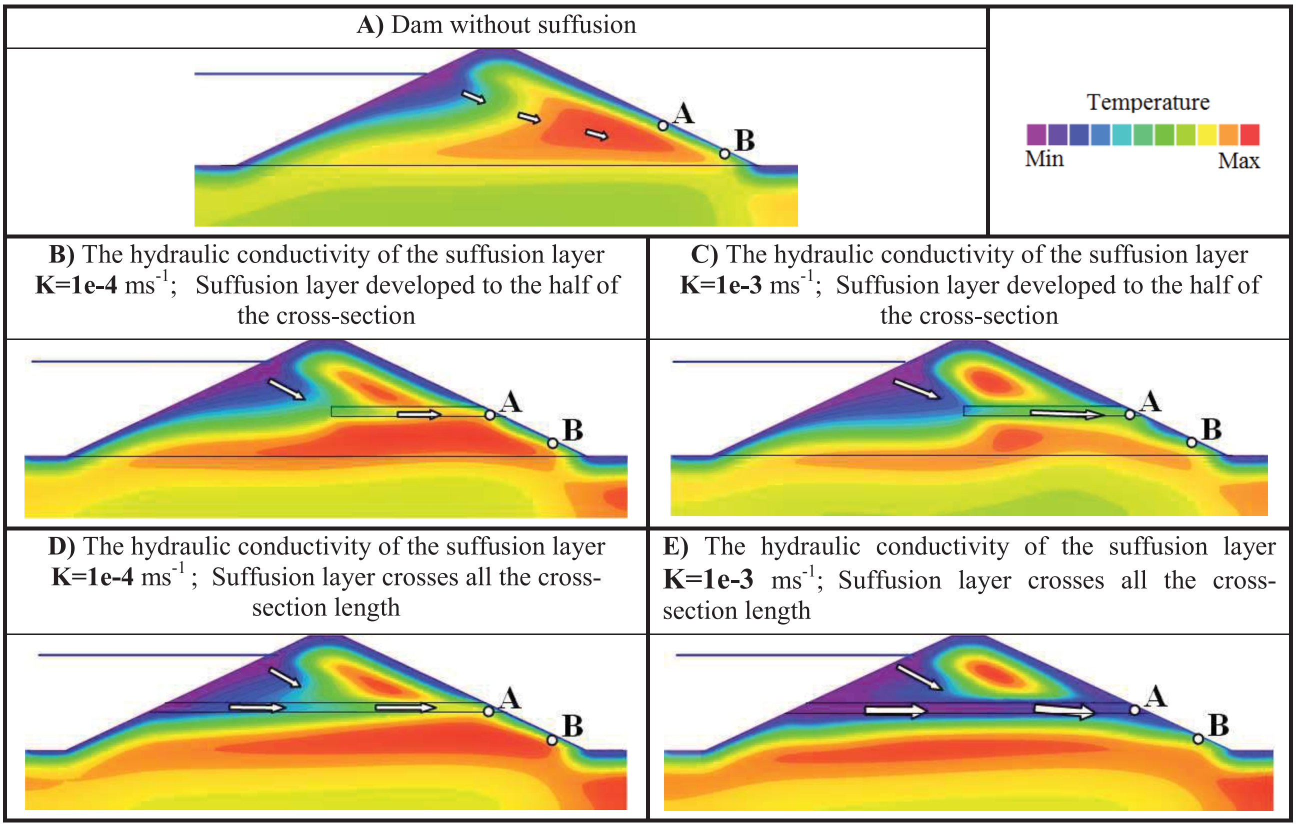

Figure 2: Temperature fields of a dam cross-section registered at the same time instant for different lengths of suffusion layer and for different values of suffusion layer hydraulic conductivity.

The appearance of the suffusion layer featuring by 1e-4 ms^{-1} hydraulic conductivity value, situated above the downstream toe, causes an small increase in the filtration velocity, and consequently a rise in heat transport from the upper part of the upstream slope towards the suffusion layer. This is illustrated by comparison of the isotherm shapes between Figure 2B (the suffusion layer developed to the half of the cross-section) and Figure 2A (the dam without suffusion). As it can be seen in Figure 2B in the area of the upstream part of the dam discussed, there is an insignificant isotherm shift towards the suffusion layer, when compared against isotherms of the thermal field shown in Figure 2A. The intensity of coupled heat and water transport in that area the more greater the longer is the suffusion layer length. However, even for the suffusion process which cuts the dam through, any isotherm shift is not very significant, as illustrated in position of isotherms in Figure 2D. Nevertheless, in the downstream part of the dam body, the suffusion layer makes horizontal the direction of the filtration velocity vectors. This direction is shown by white arrow in Figure 2B marked in the suffusion layer area. Such heading of thermal flow in the suffusion layer causes an increase in thermal influence for the reservoir heat on temperature values in the suffusion layer area next to the downstream slope. However, simultaneously, the change in the direction of the filtration velocity vectors from diagonal (dam without suffusion), into horizontal ones (dam with suffusion) in the zone of the dam downstream side, induces a slow-down in heat inflow jointly with water mass into the downstream toe.

The suffusion layer in the case under analysis acts hydraulically in the same way as a drainage does. The drainage action of the suffusion layer may be observed, amongst others, in both the variability of the saturation curve position within the dam cross-section, and the growth in the value of the filtration velocity vector towards the suffusion layer. The suffusion layer featuring by 1e-4 ms^{-1} hydraulic conductivity value causes only insignificant reduction in the saturation curve that can be seen when comparing its course in Figures 1A (dam without suffusion), and Figure 1B (the suffusion layer developed to the half of the dam's cross-section). However, for the suffusion layer with hydraulic conductivity value equal to 1e-3 ms^{-1} the influence of this layer on both the filtration field and the location of the saturation curve within the dam cross-section is mostly notable. In Figure 1C where the suffusion layer is developed to the half of the dam's cross-section the suffusion layer can be seen that is capable of the total drying the downstream zone of the dam body situated above it. The value 1e-3 ms^{-1} of the hydraulic conductivity in the suffusion layer causes significant intensification in filtration between the upstream slope and the suffusion layer, and it results in an intensive inflow of the reservoir heat in depth of the upstream part of the dam body. That results in considerable isotherm shift in the upstream zone of the dam body that can be seen when comparing thermal fields between Figure 1B and 1C and between Figure 1D and 1E. The longer the suffusion layer the more higher the intensity of coupled heat and water transport. Likewise in the case described before, in which the soil the suffusion layer hydraulic conductivity was 1e-4 ms^{-1}, also for the hydraulic conductivity in the erosion layer that amounts to 1e-3 ms^{-1}, the suffusion makes horizontal the filtration and heat flow in the downstream body part. However, for the suffusion layer featuring by the hydraulic conductivity 1e-3 ms^{-1}, the intensity of the hydro-thermal flow is so high that in the vicinity of the downstream slope it influences not only temperature directly in the suffusion layer zone, but also significantly impacts temperature of the downstream toe. Direction of these impacts is illustrated by diagonally directed white arrows marked in the downstream zone of the erosion layer in Figures 1C and 1D.

Note that the conclusions presented above relate exclusively to the dam case under analysis. Description of the thermal-hydraulic field picture will look differently when the suffusion layer develops at the junction of the dam foundation and its body, or directly in the dam downstream toe.

IV BACKGROUND OF IRFTA MODEL

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 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.

$$C\frac{\partial T}{\partial t}-\lambda\frac{\partial^2 T}{\partial x^2}-vC^f\frac{\partial T}{\partial x}=0\,, \tag{1}$$

where T is temperature, C is the volumetric heat capacity of porous domain, C^f is the volumetric heat capacity of water, λ defines the thermal conductivity of porous domain and v is the water flow velocity.

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

$$y(t)=\left(h*a\right)(t)=\int_0^t h(t-\tau)\,a(\tau)\,d\tau\,, \tag{2}$$

where * is the mathematical convolution operator.

In other words, the impulse response function describes how the input signal (in form of Dirac delta) is modified by the porous zone of the dam. In our model we applied approximation of the impulse response function in the form of a two-parameter (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, the η representing the time-lag, which quantifies time elapse between the onset of the loading and the response of the system in measuring point, and the α is the signal damping factor. The values of the α parameter fall within 0 - 1 interval. Thus, where α is 0, the signal has been entirely suppressed. A rise in the α parameter value means a reduction in signal attenuation, down to the 1 value, thus meaning the signal amplitude in measurement point equals to that of the input signal.

Finally the IRFTA model has the following form :

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

where θ_C is the constant, θ_w and θ_{air} define the impulse response function approximation for the water temperature and the air temperature, respectively, and the R_w and R_{air} are the water temperature and air temperature loadings on the dam surface, respectively.

The *T(x,t)* temperature measurement taken is formed by superposition of the responses from the dam to the water temperature and the air temperature loadings that are represented in the second and the third term of equation (4), respectively. Finally the IRFTA model has four parameters, while two of them α_w and η_w inform about transformation of the thermal signal from the upstream face (water temperature loading). Modification of the downstream thermal signal (air temperature loading) is described by the next two parameters α_{air} and η_{air}.

V RESULTS OF THE IRFTA MODEL APPLICATION

V.1 Introduction to the modelling performed with the IRFTA model

The temperature series taken for 4 months at two points situated within the downstream part of the dam cross-section, as described in Sections II and III, were then modelled with application of the IRFTA model. Modelling the temperature measurements was performed as a function of both the reservoir water temperature and the air temperature there over. The measuring points are marked in Figures 1 and 2 as the A and the B points. The A point is situated directly in the suffusion zone, at 5.25 m altitude above the dam base, and at 0.5 m horizontal distance from the downstream slope. The B point is situated in the dam downstream toe, at 1.5 m altitude above the dam base, and at 0.5 m horizontal distance from its downstream slope.

The values of the IRFTA model parameters obtained in modelling exercises for points A and B are shown in Table 1 and Table2, respectively. The Tables show comparison of parametric values obtained for modelling a suffusion-free dam and a dam with the suffusion layer, the hydraulic conductivities of which are 1e-4 ms^{-1} and 1e-3 ms^{-1}, respectively, for two cases of the suffusion layer length, each time. For the first case, the suffusion layer developed to the dam half of the cross-section, whereas for another one, the suffusion layer entirely cuts the dam cross-section between its downstream slope and the upstream slope. Each individual Table row contains entry of the *R2* coefficient of determination values, and then those of the IRFTA α_w and η_w and α_{air} and η_{air} model parameters which describe the thermal signal transformations upcoming from the upstream and the downstream slopes, respectively.

For all cases of the modelling results presented, the values of the *R2* coefficient of determination are close to 1, meaning the data reproduction by the model is almost ideal. The value of the R2 coefficient equal to 1 would mean full reproduction of the data modelled wheras 0 would stand for lacking correlation between data and model.

V.2 Results of the IRFTA-modelled temperature measurements taken from the A point

Transformation of thermal signal between the upstream slope and the A point

The A point is situated just in the suffusion zone. The analysis of the values of model parameters obtained, as presented in Table 1, shows that the influence of thermal signal upcoming from the upstream part on temperature in the A point increases (the α_w value growing) with growing suffusion layer length, or with increase in the value of the hydraulic conductivity the suffusion layer, and simultaneously, the elapse time η_w of this signal upcoming to the A point decreases most considerably.

The influence of thermal signal upcoming from the upstream part is mostly growing during the initial phase of an increase in the suffusion layer length. The α_w is 0.13 for suffusion-free dam, whereas for the suffusion layer developed to the half of the cross-section its value rises up to 0.4 and 0.45 for the hydraulic conductivity values in suffusion layer amounting to 1e-4 ms^{-1} and 1e-3 ms^{-1}, respectively, whereas the change in the α_w value becomes negligibly low as the length of the suffusion layer is further growing.

In turn, the η_w signal elapse time from the upstream slope is 130.72 days for suffusion-free dam layer, and it decreases first to 109.57 and then to 87.72 days, as the suffusion layer length grows, the hydraulic conductivity of which is 1e-4 ms^{-1}. Analogously, the η_w decreases from 130.72 days, by 34.43 days, to only 5.76 days (i.e. more than twenty times as much) when the suffusion layer hydraulic conductivity is 1e-3 ms^{-1}.

IRFTA model's parameters		**Dam without suffusion**	**Hydraulic conductivity of the suffusion layer K=1e-4 ms^{-1}**		**Hydraulic conductivity of the suffusion layer K=1e-3 ms^{-1}**	
			Suffusion layer developed to the half of the cross-section	Suffusion layer crosses all the cross-section length	Suffusion layer developed to the half of the cross-section	Suffusion layer crosses all the cross-section length
Coefficient of determination	***R2***	0.976	0.991	0.992	0.998	0.999
Water heat influence	α_w [ ]	0.13	0.4	0.4	0.45	0.44
	η_w [days]	130.72	109.57	87.72	34.43	5.76
Air heat influence	α_{air} [ ]	0.6	0.54	0.54	0.42	0.44
	η_{air} [days]	0.34	0.15	0.11	0.06	0.034

Table 1: The values of the IRFTA model parameters obtained from modelling the temperature series taken in the A point.

When analysing in details the influence of the change in the suffusion layer hydraulic conductivity on the values of the IRFTA model parameters one can note that the η_w is 130.72 days for a suffusion-free dam layer (the value the hydraulic conductivity being then 1e-5 ms^{-1}), but when the suffusion layer length further advances up to the half of the cross-section, the η_w value decreases firstly to 109.57 and then to 34.43 days, with a change in the value of the hydraulic conductivity in the suffusion layer area, to 1e-4 ms^{-1} and then to 1e-3 ms^{-1}, respectively. Where the suffusion layer crosses all the cross-section length, the reduction in the signal elapse time between the upstream slope and the A point is yet higher and the η_w value is 87.72, and then only 5.76 days, where the value of the hydraulic conductivity of the suffusion layer changes into 1e-4 $ms^{-}1$ and then into 1e-3 ms^{-1}, respectively.

Transformation of thermal signal between the downstream slope and the A point

Examination of the variability of the IRFTA model parametric values presented in Table 1 that describe the influence of the air temperature on the A point temperature shows that attenuation of thermal signal upcoming from the downstream slope increases as the value of the hydraulic conductivity in suffusion layer grows, but it only depends to a low degree on the suffusion layer length.

When explaining this conclusion on the basis of detailed parametric values it can be noted that the α_{air} is 0.6 for a suffusion-free dam layer (the hydraulic conductivity amounts then to 1e-5 ms^{-1}). The α_{air} value decreases first to 0.54 and then to about 0.43, (thus meaning a signal damping increasing) with a change in the value of the hydraulic conductivity of suffusion layer to 1e-4 ms^{-1} and then to 1e-3 ms^{-1}, respectively, however irrespective of the suffusion layer length.

At the same time, with both an increase in the value of the hydraulic conductivity in suffusion layer, and the growth of its length, the η_{air} thermal signal elapse time from the downstream part to the A point decreases. For example, where the suffusion layer is developed to the half of the dam cross-section, the η_{air} value falls from 0.34 day, in the absence of suffusion, by 0.15 day, to 0.06 day, when the hydraulic conductivity of the suffusion layer changes from 1e-4 ms^{-1} to 1e-3 ms^{-1}. In turn, when examining the variability of the IRFTA model parameters for the case with a constant value of the suffusion layer hydraulic conductivity amounting to 1e-3 ms^{-1}, one can note decreasing the η_{air} value from 0.34 day without suffusion, during 0.06 day, to 0.034 day, when the suffusion layer length first advances to the dam axis and then to its upstream slope.

V.3 Results of the IRFTA-modelled temperature measurements taken from the B point

Transformation of thermal signal between the upstream slope and the B point

The B point is situated within the dam downstream toe. Development of the suffusion process with the hydraulic conductivity value being 1e-4 ms^{-1} causes prolongation by a dozen percent of the value of the thermal signal elapse time η_w from the upstream part to the A point with simultaneous amplification of the upstream thermal signal influence on the B point temperature (growth in the α_w parameter value).

IRFTA model's parameters		Dam without suffusion	Hydraulic conductivity of the suffusion layer K=1e-4 ms^{-1}		Hydraulic conductivity of the suffusion layer K=1e-3 ms^{-1}	
			Suffusion layer developed to the half of the cross-section	Suffusion layer crosses all the cross-section length	Suffusion layer developed to the half of the cross-section	Suffusion layer crosses all the cross-section length
Coefficient of determination	***R2***	0.996	0.995	0.994	0.998	0.998
Water heat influence	α_w [ ]	0.18	0.24	0.31	0.19	0.21
	η_w [days]	145.39	169.77	165.85	2.6	1.64
Air heat influence	α_{air} [ ]	0.6	0.61	0.61	0.59	0.55
	η_{air} [days]	0.4	0.42	0.41	0.35	0.31

Table 2: The values of the IRFTA model parameters obtained from modelling the temperature series taken in the B point.

The η_w value is 145.39 days for the absence of suffusion and it grows up to 169.77 and 165.85 days where the suffusion layer reaches the dam axis and its upstream slope, respectively. Analogously, the α_w value rises (the signal damping decreases) consequently from 0.18, by 0.24 day, to 0.31 day where the suffusion layer length is growing. The finding which relates to increase in the thermal signal elapse time η_w from the upstream slope is consistent with the conclusion included in Section III. It points out a possibility to influence from the horizontal heading of the filtration velocity vectors through the suffusion layer by the 1e-4 ms^{-1} value of the hydraulic conductivity on the time lag of the signal elapse inward the downstream toe. This time-lag is not compensated by a slight acceleration in heat transport from the upstream slope inward the downstream slope.

However, where the value of the hydraulic conductivity increases up to 1e-3 ms^{-1} the hydro-thermal relations described above alter diametrically. If this is the case, the η_w signal elapse time between the upstream slope and the B point falls by more than fifty times as much. The η_w decreases from 145.39 days (absence of the suffusion) to 2.6, and 1.64 days with suffusion reaching the dam axis and the upstream slope, respectively.

Meanwhile, the growing value of hydraulic conductivity of the suffusion layer and the increasing length of this layer cause increase (α_w growing up) in the influence of the thermal signal from the upstream slope on the B point temperature. This increase is significant for the 1e-4 ms^{-1} value of the hydraulic conductivity of the suffusion layer and becomes negligibly low where the value of the hydraulic conductivity of the suffusion layer is 1e-3 ms^{-1}.

Transformation of thermal signal between the downstream slope and the B point

The analysing of the α_{air} and η_{air} parameters recorded in Table 2 that describe the air temperature influence on the B point temperature shows negligibly low changes in their values when the suffusion layer develops, while featuring by the 1e-4 ms^{-1} hydraulic conductivity value, and the slight reduction in the signal influence

(α_{air} decreasing) on the B point temperature with simultaneous slight reduction in the thermal signal time-lag η_{air}, when the hydraulic conductivity in suffusion layer is 1e-3 ms^{-1}.

For all analyses of the modelling exercises performed for the B point as presented in Table 2, the α_{air} values are by about 30 to 40% higher than the α_w values, thus meaning the signal damping from the downstream slope significantly lower than the signal from the upstream slope.

Note that for the modelling exercises performed for the A point and presented in Table 1, the α_{air} values are meaningfully higher than the α_w values only in absence of suffusion process. For suffusion stretching between the dam axis and the upstream slope thereof this relation changes and both signals are damped from 50% to 60%.

VI CONCLUSIONS

This paper discusses relations ruling the hydro-thermal field of homogenous dam for selected case of developing suffusion process those are based on the results obtained by numerical modelling. The opportunity to modelling temperature measurements by the IRFTA model those were taken in the downstream slope zone of the dam was also examined.

The relations described in Section III above that were numerically modelled, show, in the light of developing suffusion process that the process in question has to be analysed versus, amongst others, the dam design solutions and with regard to the influence from suffusion process on location of the saturation curve within the dam, as well as to the directions and the value of the filtration velocity vectors within the dam cross-section. The suffusion process causes characteristic changes in the dam hydro-thermal field that provide for its identification through thermal monitoring.

The results of the IRFTA modelling, as presented in Section V, for the temperature series have proven the IRFTA will be an efficient tool to analyse the dam temperature measurements. Physical definitions of the model parameters have enabled a precise description of the filtration-thermal field. The IRFTA model provides for analysing temperature values measured as a function of both the reservoir water temperature and the air temperature there over that provides for its application to analysing also the temperature measurements taken close to the downstream slope.

Application of the IRFTA model for direct defining the parameters of developing suffusion process requires further tests. It needs to analyse various cases of developing suffusion process with the aim to define a complete characteristics of the influence from the suffusion process on the dam thermal field in order to enable interpretation of the value and variability of the IRFTA model parameters in the light of changing parameters in the suffusion field. Determination of the parameters of developing suffusion process seems possible, especially if the temperature measurement sensor will be situated directly in the zone of developing suffusion process.

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