

THE THERMAL MONITORING METHOD – A QUALITY CHANGE IN THE MONITORING OF SEEPAGE AND EROSION PROCESSES IN DIKES AND EARTH DAMS

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SUMMARY:

The thermal method for monitoring seepage and erosion processes qualitatively changed the monitoring of earth hydraulic structures in the scope of the detection and analysis of seepage and erosion processes. The introduction of Distributed Temperature Sensing and the development of new methods and models for temperature analysis were particularly important. Internal erosion is one of the basic threats for dams and dikes. Appropriate monitoring of this process is of key importance for ensuring the safety of these structures and minimising the costs of their possible repairs. This article describes the basics and most important issues of the thermal method for monitoring seepage and erosion processes. *Inter alia*, it presents a classification of models for passive analysis of temperature measurements in earth hydraulic structures. Particular consideration is given to essential aspects of the application of the thermal monitoring method and related recommendations

STRESZCZENIE:

Metoda termomonitoringu procesów filtracyjno-erozyjnych zmieniła jakościowo monitoring ziemnych obiektów pierzących w zakresie detekcji i analizy procesów filtracyjno-erozyjnych. Szczególne istotne było wprowadzenie rozproszonych pomiarów temperatury oraz rozwój nowych metod i modeli analizy temperatury. Erozja wewnętrzna stanowi jedno z podstawowych zagrożeń dla zapór i wałów. Właściwy monitoring tego procesu jest kluczowy dla zagwarantowania bezpieczeństwa tym obiektom oraz dla minimalizacji kosztów ich ewentualnych remontów. W artykule opisano podstawy i najistotniejsze zagadnienia w zakresie metody termomonitoringu procesów filtracyjno-erozyjnych. Przedstawiono między innymi podział modeli analizy pasywnej pomiarów temperatury w ziemnych obiektach hydrotechnicznych. Szczególną uwagę zwrócono na istotne aspekty aplikacji metody termomonitoringu oraz jej rekomendacje.

1. INTRODUCTION

Internal erosion is one of the basic threats for dams and dikes. Appropriate monitoring of this process is of key importance for ensuring the safety of these damming structures and minimising the costs of their possible repairs. A collapse of these structures causes very large material and social losses. Among the existing methods for monitoring seepage and erosion processes, the thermal monitoring method became particularly valuable and increasingly popular in recent years.

This article presents basic information concerning the thermal method for monitoring seepage and erosion processes, including a description of relations in coupled heat and water transport, temperature sensor types and the zones where temperature sensors are installed. It provides a classification of existing models for passive analysis of temperature measurements, along with a description of their most important features. Finally, it describes particularly important experiments and aspects of the application of the thermal monitoring method and related recommendations.

2. BASICS OF THE THERMAL MONITORING OF SEEPAGE AND EROSION PROCESSES

2.1 Coupled heat and water transport

Thermal methods for analysis of water flow in soil are based on coupled relations between heat and fluid transport processes. These dependencies are described by the energy conservation equation.

For 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 alone can significantly affect local thermal front velocities. In turn, in the case of fluid motion (seepage, leakage), heat is also transported along with the water mass. This process is called advection and generates a much more substantial heat flow than the one caused by the conduction process; which is the higher the faster the fluid flow is.

In turn, the internal erosion process directly affects the values and directions of the seepage

field vectors and, in consequence, the heat transport. Moreover, the basic types of erosion processes (suffusion, hydraulic breakthrough, contact zone erosion) have characteristic features of their time and space development, demonstrated through the seepage field, also in the temperature field (Radzicki and Bonelli, 2010b and 2012).

Because of these relations, the thermal monitoring method enables the detection and analysis of both seepage processes, including leakages, and erosion processes.

As an example, Fig. 1 shows a numerical analysis of the impact of the different suffusion process development stages on the thermal field of a dam cross-section at the same time instant of the same structure under the same thermal and hydraulic loadings. It can be clearly seen that the heat flow from the reservoir into the structure body grows in the area of the highest hydraulic gradients as the erosion process develops.

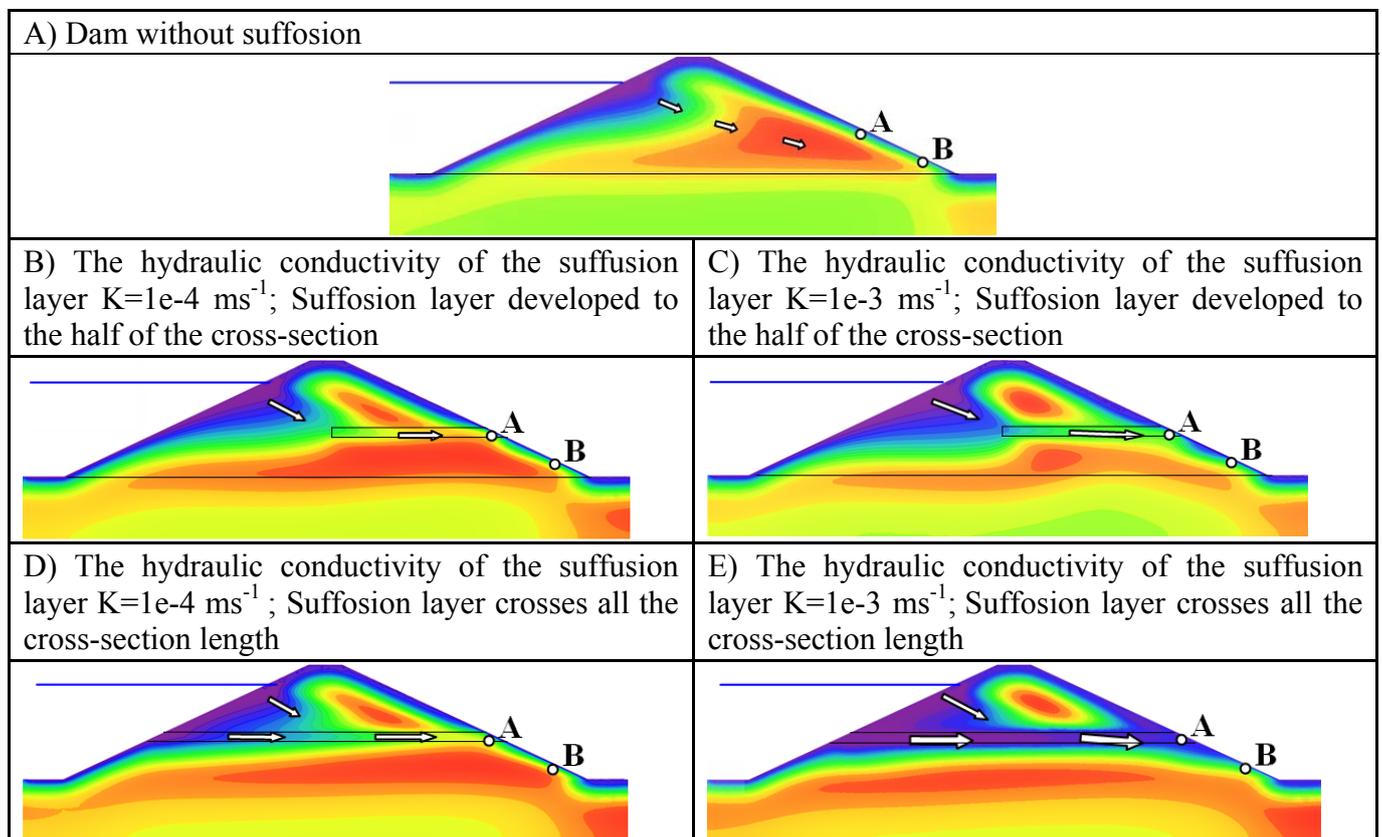


Fig. 1. Temperature fields of a dam cross-section registered at the same time instant for different lengths of suffusion layer and for different values of suffusion layer hydraulic conductivity (Radzicki and Bonelli, 2012).

2.2. Temperature measurement methods

In the early period of the development of thermal monitoring methods, temperature measurements were carried out with single temperature sensors installed in the body or the foundation of a structure, usually in the course of its construction or repair, or with water temperature measurements in piezometers. In the latter case, the measured vertical water temperature profile represents the vertical ground temperature profile round the piezometer, under certain assumptions, including the one that the impact of convective water movements on the heat distribution in the piezometer is negligibly small.

However, one of the reasons for the success of the thermal monitoring method was the application of linear temperature measurements. The capacity to carry out continuous measurements all along the structure brought about a quality change in the monitoring of seepage and erosion processes compared with the point monitoring carried out only at selected places of the structure.

One of the linear technologies applied in thermal monitoring is Distributed Temperature Sensing (DTS) using a fiber optic as a temperature sensor. A laser impulse is fed into a fiber optic. As the light crosses the fiber optic core, photons are dispersed on its molecules. Some of the photons return to the point where the impulse was transmitted, as the so-called backscattering. The spectral analysis of backscattering and its comparison with the spectrum of the light fed into the fiber optic enables, *inter alia*, the determination of the temperature of the fiber optic at the point where the backscattering emerged (Vogel, 2001). At present, the system used to monitor hydraulic structures makes it possible to measure the temperature of a fiber optic with a spatial resolution of one metre and enables temperature measurements with a resolution of at least 0.1°C over a section of one cable up to 20 km long. The fiber optics applied to measure temperatures on hydraulic structures have watertight, armoured jackets. This ensures their easy installation on the construction sites, tightness, very high strength and durability of at least several dozen years (Radzicki, 2009).

A technology alternative to fiber optics is the solution which will be called the “multi sensor cable” technology. This entails a cable inside which single temperature sensors and communication and supply cables have been placed and integrated. In such a cable, single temperature sensors are distributed along its length at constant or individually set intervals. The distance between sensors must be so selected as to ensure “quasi” continuous measurements which match fiber optic sensors as regards their spatial resolution. The main advantage of this solution for short measurement sections of up to several hundred metres is its cost which is even several times lower than that of a fiber optic-based thermal monitoring system. An example of such a “multi sensor cable” is MCableS © from Neostrein. In addition to its installation along a structure, the “multi sensor cable” technology is also applied in water temperature measurements in piezometers. Given its small diameter, a “multi sensor cable” does not prevent manual periodical measurements in a piezometer, which are more often than not required for dams in order to verify automatic pressure measurements.

The combination of continuous temperature measurements along a damming hydraulic structure and vertical measurements of temperature profiles carried out in selected cross-sections of the structure enables a more detailed analysis of destruction processes in the cross-section of interest here. After a destruction process has been detected to develop along the hydraulic structure using the linear measurement method, additional vertical temperature measurements can be carried out in this cross-section. Depending on the needs, the abovementioned method for water temperature measurements in a piezometer can be applied for this purpose; however, particularly in the case of hydraulic structures which periodically dam up water, such as e.g. flood control dikes, sensors which are driven or drilled directly into the ground can be used.

2.3 Location of sensors in the cross-section of a damming hydraulic structure

Temperature sensors are installed primarily near or directly within the hydraulic structure zones designed to capture and direct a leakage; thus, especially near drainages and filters, as well as on the land side of waterproof elements, such as the fill, outer and inner waterproof elements.

Given the fact that damming hydraulic structures are different from one another, *inter alia*, in terms of size (scale), geometry, construction solutions and foundation conditions, the determination of their location always requires an individual analysis, carried out by an experienced specialist in the field of thermal monitoring of damming hydraulic structures. It is based e.g. on specialist hydrothermal numerical modelling of the hydraulic structure analysed.

However, in general, we can distinguish three typical zones of the installation of temperature sensors in the body of a hydraulic structure, marked successively in Fig. 2 as Zones A, B and C.

Implementation of thermal monitoring in more than one of the aforementioned zones enhances the opportunity to very early detection of both leakage and erosion, and provides for the likelihood to accurate determination of their pathways.

It has to be emphasised that the cost of the linear temperature sensor is negligibly low, when compared against the costs of the structure construction or the repair costs. Thus, those have to be always installed in newly constructed structures, as well as on the occasion the existing structures repairs, particularly when repairing the waterproof or drainage components.

The upstream part of the structure body (A Zone) - Monitoring this zone can be done in all earth hydraulic works, the impervious membrane of which is located on the upstream side. Linear temperature sensor could be installed in this zone either during repair work on the membrane of existing structure or when building new structure. In order to monitor

leakages through the membrane into the body mass, a linear temperature sensor is installed on the downstream side of the impervious upstream membrane. Thermal monitoring of this zone in question provides for early identifying of even a minimum point leakage in the membrane, as little as only 0.2 l/min/1m (Cunat 2010, Radzicki 2009).

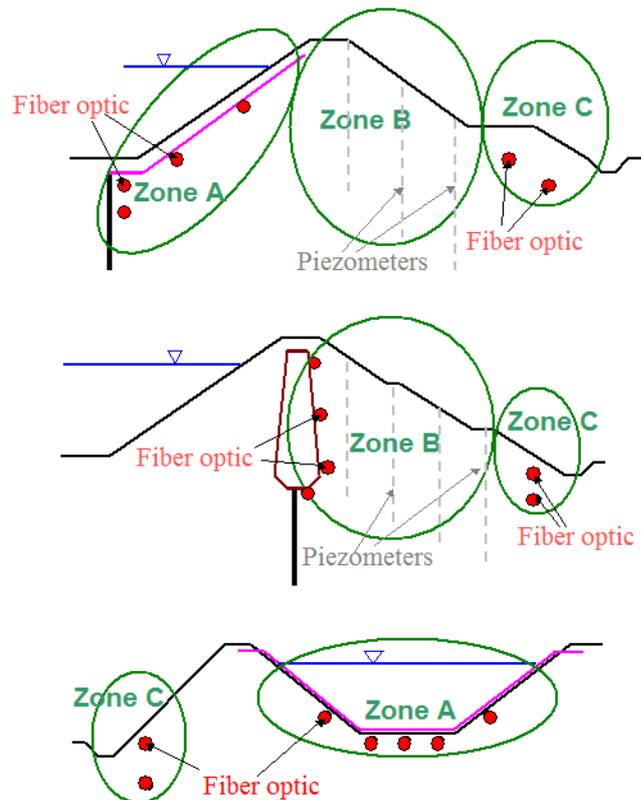


Fig. 2. The typical locations of the temperature sensors in the thermal monitoring method.

The central part of the structure body (B Zone) - Installing a linear temperature sensor in this zone could be possible during construction of a structure or its considerable redevelopment. If there is a waterproof element in this zone, e.g. the core, then the linear temperature sensor is to be installed on the downstream side of waterproof element, usually in its filter and drainage. Where installation of the temperature sensor is not possible, then the thermal monitoring could be carried out with use of temperature sensors installed in piezometers.

The downstream toe of the structure (C Zone) - For existing structures, installation of a linear temperature sensor in the structure downstream toe is the most cost-effective solution which provides for continuous

monitoring alongside the structure length, with parallel minimum scope of the earthwork. It is this structure zone in which a leakage commutation occurs usually, particularly, if drainage is placed therein. Tests performed on the research embankment in the 1:1 real scale proved the opportunity to detect 2l/min leakage in this zone (leakage discharge measured in the upstream bank) (Cunat, 2010; Radzicki and Bonelli, 2010a).

2.4 Passive and active thermal monitoring

Two basic types of thermal monitoring methods can be distinguished – passive and active.

In passive thermal monitoring, the natural temperature of a structure is analysed. The temperature at the measurement point is primarily determined by external thermal loadings. On its way from the structure slopes to the measurement point, a thermal signal is modified depending on the values of the parameters of the medium which it has crossed; thus, it contains information on this medium, particularly the information concerning the seepage and erosion processes unfolding in it. In consequence, a passive thermal monitoring method enables the monitoring of the whole cross-section of the structure and the analysis of the seepage and erosion processes unfolding in it (Radzicki 2009).

In active thermal monitoring, in addition to a temperature sensor, a heat generator is also inserted into the ground. In the case of linear temperature sensors, it can be metal wire which is heated using electrical resistance. With appropriate calibration the examination of heat distribution enables the determination of the seepage velocity round the sensor (Pelzmaier et al. 2006). However, the range of the active method depends, *inter alia*, on the parameters of the ground medium and primarily on the measurement time. Usually, it reaches several centimetres, whereas after long heating for many hours it can be enhanced to several dozen centimetres.

The choice of a thermal monitoring method – e.g. whether to use a passive method only or to apply a passive method, along with an active

method as a supplementary one – requires a case by case analysis to be carried out by an experienced specialist in the field of the thermal monitoring of hydraulic structures, by means, *inter alia*, of specialist hydrothermal numerical modelling of the structure analysed.

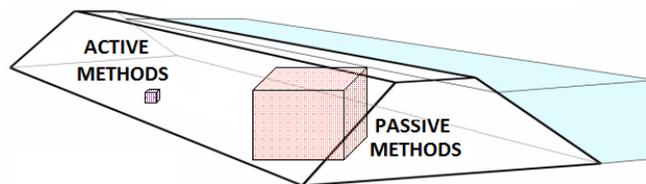


Fig. 3. Schematic comparison of the leakage detection zone ranges ensured by passive and active temperature measurements for a single measurement point

2.5 Passive methods and models for measurement analysis

Thermal methods for leakage detection in earth dams have been used for more than twenty years (Johansson, 1997). Nevertheless, for a long time their application was limited mainly to analyses of the body zone situated deep inside the dam in which the impact of air temperature was negligibly small. The simultaneous impact of water and air temperatures on the measured temperature could even prevent correct interpretation of results. The analysis of temperature measurements was based mainly on simple methods, enabling the comparison of the measured data taking into account different locations of the sensors or differences between measured temperature time series, or on the comparison of body temperatures with those calculated in the absence of a seepage, e.g. (Konrad et al. 2000). In consequence, non-advanced signal analysis methods entailed significant limitations affecting the readability of the information contained in a thermal signal (Radzicki, 2009).

At present, important methods for the analysis of temperature measurements include specialist models most of which were elaborated in the last six years. The basic differences among them relate to the minimum length of temperature measurement series and the range of result analyses. Fig. 4 shows a

systematised classification of the considered models as proposed by Radzicki (2011) and their basic features.

On the one hand, there are statistical models based on signal analysis methods which only enable the identification of the leakage location. An example of this type of tool is the Daily Analysis Model developed by EDF to analyse temperature measurements, enabling automatic and quick leakage detection, including flood control dikes.

On the other hand, there are also models which require temperature measurements to be carried out for a longer time, but which enable the determination of the parameters of the seepage processes, which is of key importance

for experts who assess the condition of earth dams and canal dikes. Example of this type of model is the IRFTA model. This model enables leakage identification; but primarily it makes it possible to determine the intensity of seepage processes in the dam and to assess the dynamics of their development.

In turn, the amplitude model, developed in 1997, requires one-year temperature measurements and entails many limitations to its application, including, *inter alia*, the hypothesis of absence of the impact of air temperatures on measurements; still, it enables the estimation of the seepage velocity in the suffusion layer in an earth dam.

General models division		Signal processing models	Models with the physical meaning of the parameters		
Nazwa modelu	Daily Analysis Model	Source Separation Model	Impulse Response Function Analysis Models		Amplitude Model
			IRFTA	MORITO	
Minimal period of the temperature data acquisition		about 1 day	about 2-3 months		1 year
Range of the application	Type of the hydraulic structure	Earth dams, dikes of the canals and flood protection levees	Earth dams and dikes of the canals		
	Hydraulic conditions	Saturated and unsaturated zone			Only saturated zone
	Thermal conditions	Analysis in relation to the reservoir temperature and air temperature as well to the other thermal sources.	Analysis in relation to the reservoir temperature and the air temperature.		Analysis only the dam's reservoir temperature influence; air temperature influence must be neglected
Method principle		Data daily analysis developed using signal analysis methodology	Source separation method	Modeling with an exponential approximation of the impulse response function of the system	
Main advantages		The fastest leakage detection method. Possibility of the early warning, automatic leakage detection system installation	Leakage detection method	Parametrical evaluation of the coupled heat and water transport, including leakage detection possibility and its intensity assessment MORITO model allows to filter out sinusoidal, seasonal annual temperature variation	
Described examples of the model application		Beck et al., 2010	Beck et al., 2010; Khan et al., 2008	Radzicki, 2009; Radzicki and Bonelli, 2010a; Artières et al., 2007	Beck et al., 2010; Cunat, 2012
					Johansson, 1997

Fig. 4. Division and main features of passive temperature analysis models (Radzicki, 2011)

3 ESSENTIAL ASPECTS OF THE APPLICATION OF THE THERMAL MONITORING METHOD

The effectiveness and practicality of the thermal monitoring method have been validated by a large number of its applications on existing hydraulic structures and real-scale tests at research basins. Numerous examples of these applications have been presented in professional literature. A particularly important

fact was the confirmation of the effectiveness of the detection and analysis of seepage and erosion processes for temperature sensors situated in the landside toe of the structure, i.e. where it is relatively cheap and easy to install a sensor at an existing structure, but, at the same time, this is often an unsaturated or partly saturated zone, more often than not with a dominating impact of air temperature on the temperature of this zone.

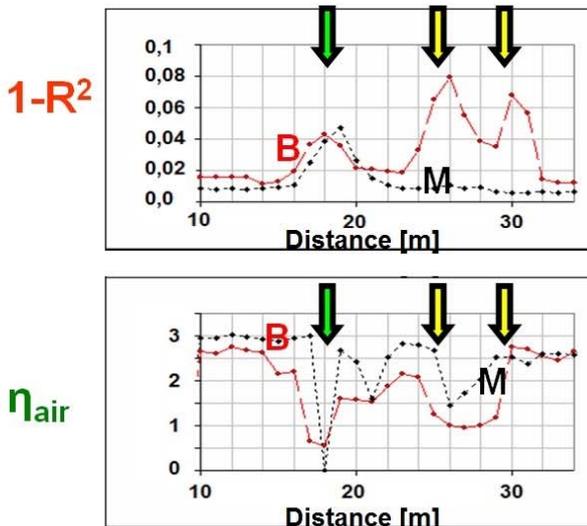
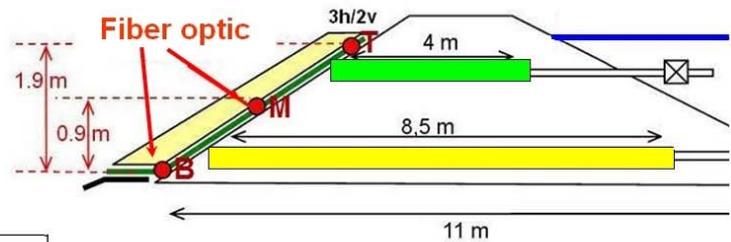


Fig. 5. Leakage detection based on the IRFTA model at the PEERINE experimental basin (Radzicki and Bonelli 2010a)

The application of the IRFTA model to analyse the degree of advancement of seepage processes in hydraulic structures designed for continuous damming was presented e.g. by Radzicki and Bonelli (2010a). They analysed temperature measurements carried out in the derivative channel at Oraison in France, of the EDF Company, which had also installed a fiber optic cable in the toe of the structure. As a result of modelling, over the length of the section examined, five hydrothermal zones were identified which were directly related to the different degree of advancement of seepage processes. Analysis of the parameters of the

model enabled the physical interpretation of the course of the processes considered and made it possible to determine their intensity. In turn, Fig.5 shows an example of leakage detection using the IRFTA model during tests carried out at the PEERINE experimental basin (Irstea, Aix-en-Provence, France). Importantly, in this case Radzicki and Bonelli (2010a) demonstrated that this model enabled effective detection even of very small leakages which caused only a change in the moisture content of the ground in the landside toe zone.

A very important test was the IjkDijk Project implemented in the Netherlands in 2009. It

consisted in the verification of different methods for piping detection and monitoring. Using real-scale dike models, tests on the development of piping were carried out at the contact zone between the dike body and foundation. Four tests, 4 to 6 days long, were conducted, each time lasting until the collapse of the structure, i.e. a breach of the earth dike. In these tests, the application of fibre optic temperature sensors made it possible for the first time to accurately visualise in time the course of the piping process in the real scale of the damming hydraulic structure. The analysis of temperature measurements by the Daily Analysis Model developed by EDF (France), which had been carried out for data measured by a fibre optic cable installed in the landside toe of the structure (Beck et al., 2010), proved to be particularly valuable. The Daily Analysis Model, which could operate in an automatic mode, localised points of the zones where the erosion process developed, even several days prior to the collapse of the structure.

Due to the positive experiences in the application and testing of the thermal monitoring method, these methods were recommended, *inter alia*, by the International Commission on Large Dams (ICOLD) in its Bulletin (ICOLD, 2013) No. 164, prepared by the European Working Group (EWG) on Internal Erosion of ICOLD: “... *classical methods are more likely to be effective for backward erosion, suffusion and contact erosion. Concentrated leak erosion may progress rapidly in many situations. Many less direct means of detecting seepage are now available. The most promising is temperature measurement which can be used to infer localized flow. Fiber optic cables facilitate data collection and make it possible to cover large parts of the dam. Remote sensing options also offer great potential in detecting whether the seepage has caused erosion*”. Moreover, Professor Fry, who had for many years been the President of this Commission Working Party, wrote that (Fry, 2012) “... *a suitable method for detecting internal erosion consists in taking a series of measurements in real time along the whole length of the embankment. The*

goal is to detect any kind of anomalies, interpret them in real time with the participation of expert systems and compare them to several safety criteria... in our opinion, Distributed Fibre Optic Temperature measurement is the best method suited to achieve these goals” and “Temperature measurement in dam body is the best detection of leaks at small and medium depths”

The above quotations recommend the thermal monitoring method for detection of both seepage (leakage) and erosion processes. They underline the spatial continuity of monitoring carried out by this method.

Early and accurate detection of destruction processes is of key importance for minimising the risk of a breakdown and collapse of a structure. It can also greatly contribute to reducing the costs of a possible repair which would be limited to accurately defined zones of the yet insignificantly developed erosion process. Analysis of the degree of development and dynamics of the erosion process in time, carried out by a hydro-engineering expert using the thermal monitoring method, enables a more accurate assessment than before of the condition of a structure all along its length. In turn, the application of the thermal monitoring method on a group or system of damming hydraulic structures managed by one operator or institution will enable optimisation and economisation in the planning and management of the operation and repairs of these structures.

6. CONCLUSIONS

The effectiveness of the thermal monitoring method discussed above is due to the simultaneous development of temperature measurement methods, as well as methods and models for analysis of temperature measurements. The basic advantages of this method include early and accurate leakage detection, continuous monitoring all along the structure and the possibility of setting up a thermal monitoring installation at already existing structures, particularly in their landside toe. Given the systematically growing

number of such installations all over the world and the fact that it has been recommended by the ICOLD, a great increase in the number of applications and dissemination of the thermal monitoring method in the practice of the monitoring of damming hydraulic structures can be expected.

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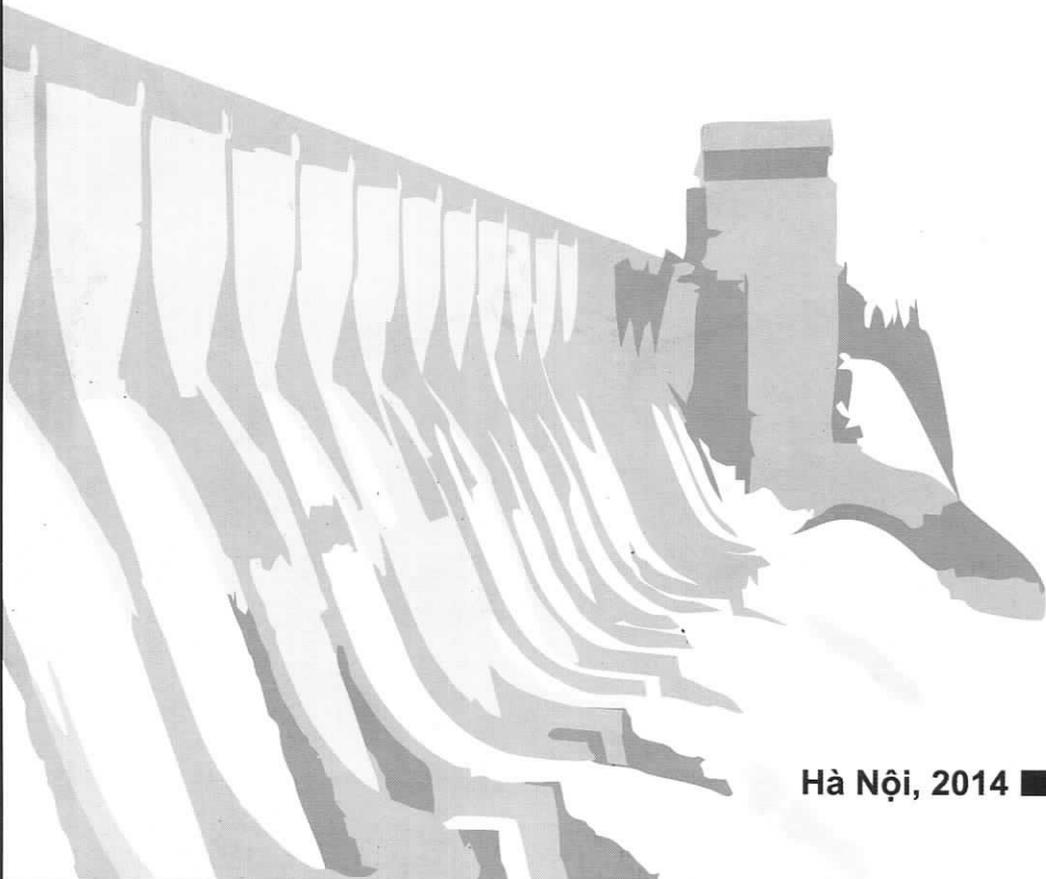
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