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AN INNOVATIVE 3D SYSTEM FOR THERMAL MONITORING OF SEEPAGE AND EROSION PROCESSES AND AN EXAMPLE OF ITS USE FOR UPGRADING THE MONITORING SYSTEM AT THE KOZŁOWA GÓRA DAM IN POLAND (*)

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1. INTRODUCTION

Although the thermal monitoring method which is briefly outlined in Section 2 is an effective, recognised and recommended method for the detection and assessment of seepage and erosion processes, the implementation of this method in the general practice of monitoring the existing damming structures, such as dams, channel embankments and flood protection dykes, has been slow. Exact information concerning the location, spatial pattern and dynamics of seepage and erosion processes is of great significance for minimizing the operational costs of damming structures, including the optimization of the management of their repairs, and for minimizing their extent and costs. At the same time, it is of key importance for carrying out correct assessments of the condition of these damming structures and their safety. From this point of view,

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(*) *Système 3D innovant pour la surveillance thermique des processus d'infiltration et d'érosion, et exemple d'utilisation pour améliorer le système de surveillance du barrage de Kozłowa Góra en Pologne* the costs of thermal monitoring systems are not high when compared with the whole outlays and profits.

However, these benefits are not always a sufficient argument in the light of the budgets of the entities managing these damming structures for their operation which are limited for different reasons or as a result of the different policies of managing them which are pursued on ad hoc basis. From this point of view, the cost of a DTS (Distributed Temperature Sensing) unit which is required for fibre optic-based temperature measurements may be one of the reasons for the limited extent of the application the thermal monitoring method. Its cost is less important for longer measurement sections when it is spread for several or more kilometers of the damming structure monitored. Yet another, more important reason is the cost of earthworks needed for the installation of a fibre optic cable in the body of the existing damming structure or in the ground underneath it. Moreover, in addition to the budget constraints, in certain cases the earthworks needed for installing cables are not feasible because of the threat which they pose for the safety of a dam or dyke.

The above reasons provided the basis for starting a grant project in 2012, consisting in the cooperation among Polish entities, the Neostrain Company and the Cracow University of Technology, for the purposes of developing an innovative, integrated thermal monitoring system which would be characterized by:

a) a low cost of systems and their installation, particularly at the existing damming structures,
b) simple, no-excavation installation,
c) the continuous thermal monitoring of seepage and erosion processes all along the damming structure, together with the possibility of carrying out vertical temperature profile measurements at cross-sections of the damming structure where these processes have been found to intensify,
d) the measurement resolution along the damming structure which is comparable to that of fibre optic-based thermometric measurements,

This project produced a 3D thermal monitoring system (Therm3Detect®), the basic assumptions and features of which are presented in Section 3. E.g. this system was installed in the middle of 2014 on the Kozłowa Góra Dam in Poland in order to assess exactly the course and dynamics of the intensified seepage and erosion processes on this dam, which are described in Section 4, along with the basic characteristics of this dam. Sections 5 present details of upgrading the monitoring system installed on the Kozłowa Góra Dam and the first measurements carried out in it.

2. THE METHOD FOR THERMAL MONITORING OF SEEPAGE AND EROSION PROCESSES

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, 2010a 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 modelling 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.

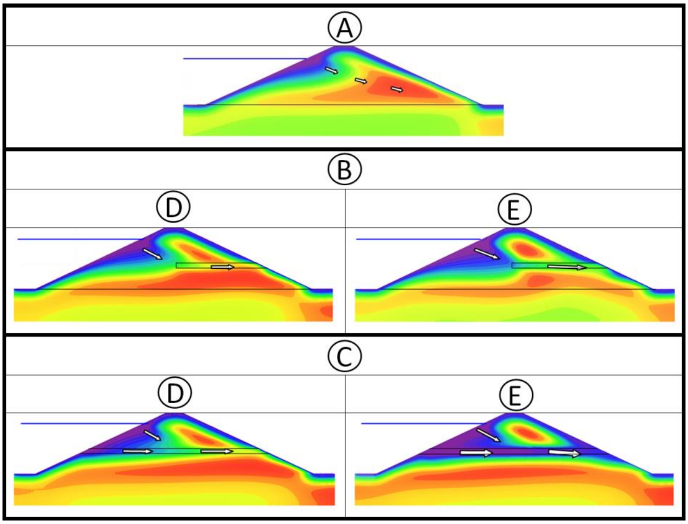

Fig. 1
Temperature fields of a dam cross-section registered at the same time instant for different lengths and for different hydraulic conductivity values of suffusion layer (Radzicki and Bonelli 2012)
Champs de température d'une coupe de barrage enregistrée au même moment pour différentes longueurs et pour différentes valeurs de perméabilité hydraulique de la couche de suffusion (Radzicki and Bonelli 2012)

(A)	Dam without suffosion	*(A)*	*Barrage sans suffusion*
(B)	Suffosion layer developed to the half of the cross-section	*(B)*	*Couche de suffusion développée à la moitié de la coupe*
(C)	Suffosion layer crosses all the cross-section length	*(C)*	*Couche de suffusion traverse toute la longueur de la coupe*
(D)	Hydraulic conductivity of the suffusion layer K=1e-4 ms^{-1}	*(D)*	*Perméabilité hydraulique de la couche de suffusion K=1e-4* ms^{-1}
(E)	Hydraulic conductivity of the suffusion layer K=1e-3 ms^{-1}	*(E)*	*Perméabilité hydraulique de la couche de suffusion K=1e-3* ms^{-1}

Thermal methods for leakage detection in earth dams have been used for more than twenty years (Johansson, 1997). 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 or by vertical water temperature profile measurements in the piezometers which represents the vertical ground temperature profile round them. In recent years, these methods were substantially developed in terms of both the temperature measurement and analysis methods, enabling an early detection and assessment of the dynamics of seepage and erosion processes and in many cases they make it possible to calculate the seepage velocity. Due to the positive experiences in the application and testing of the thermal monitoring method, these methods were recommended, inter alia, in Bulletin (ICOLD, 2013) of the International Commission on Large Dams (ICOLD)

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 fibre optic as a temperature sensor (Vogel, 2001). At present, the system used to monitor hydraulic structures makes it possible to measure the temperature of a fibre optic with a spatial resolution of one meter and enables temperature measurements with a resolution of at least 0.1ºC over a section of one cable up to tens of kilometers long. The fibre optics applied to measure temperatures on hydraulic structures have watertight, armored jackets. A technology alterative to fibre 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 fibre optic sensors as regards their spatial resolution. The main advantage of this solution for short measurement sections of up to several hundred meters is its cost which is even several times lower than that of a fibre optic-based thermal monitoring system. However, just as in the case of fibre optic cables, the application usually requires the performance of earthworks.

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 landside or downstream side of waterproof elements. For the existing dams, installation of a linear temperature sensor in the structure downstream toe is cost-effective solution which provides for continuous monitoring alongside the structure length, with parallel minimum scope of the earthwork. 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 analyzed.

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 (Radzicki, 2009). There are many diverse methods for the analysis of passive measurements in which advanced methods for analysis of temperature time series play an important role (Beck *et al*. 2010, Radzicki and Bonelli 2010b). They were listed, classified and their characteristic features were presented by Radzicki (2011, 2014a). 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 heating according to Joule low. With appropriate calibration the examination of heat distribution enables the determination of the seepage velocity round the sensor. However, this method also has a number of constraints. One of them is a lesser extent of detection in space than the passive method. It also requires much more energy (Pelzmaier *et al* 2006, Courivaud, 2012). 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 analyzed.

3. INNOVATIVE 3D THERMAL MONITORING SYSTEM

Due to the measurement solutions applied in it, the Therm3Detect® of three dimentional thermal detection and monitoring of leakages and erosion processes, which was developed within the framework of the previously mentioned research and development cooperation between the Neostrain Company and the Cracow University of Technology, enables the continuous thermal monitoring of seepage and erosion processes all along the damming structure, particularly in its downstream toe. It is complemented by measurements of vertical temperature profiles at cross-sections of the damming structure, particularly those where intensified seepage and erosion processes are found. This system allows for the optimum combination of the detection and preliminary analysis of seepage and erosion processes all along the damming structure with an more detail analysis of the course and dynamics of these processes at the cross-sections where they have occurred.

The Therm3Detect® system is based on two basic types of sensors: MCableS® and MPointS®. MCableS® (Multipoint Cable Sensor) are measuring cables integrated with sensors and transmission and supply systems, which were already described briefly in Section 2. MCableS® are used when repairs of damming structures are carried out or when they are rebuilt and it is possible to take an advantage of the planned earthworks to install the sensors. MCableS® are also used to measure the vertical temperature profiles in piezometers, if they have been installed at the damming structure. The cost of a system using multi sensor cables at measurement sections up to 1 km long may be even several times lower than that of a fibre optic thermometric system. Still, it is the MPointS® (Multi Hammered Points Sensor) sensors that are the key elements of the Therm3Detect® system. They are mounted without an excavation by inserting successive sensors in a series, one after another. They make it possible to install a system for carrying out both the quasi-continuous thermal monitoring all along the damming structure, particularly in its downstream toe, and vertical measurement profiles – both with any density of temperature sensors in space, not exceeding 1 m. The resolution of the spatial distribution of measurement points for MPointS® sensors is adapted on a case by case basis to each damming structure and the possible scenarios of seepage and erosion processes so as to enable the detection of erosion processes at an early stage of their development in a continuous manner all along the damming structure. The sensors are characterised by a small diameter and their mounting does not leave a large hole. Still, after a sensor has been installed, the hole is secured, *inter alia*, by filling it with bentonite granulate, which is wetted with water when it is inserted successively. It is easy and cheap to “replace” a damaged sensor in the Therm3Detect® system. Near a damaged sensor, a new sensor is inserted and incorporated into the system.

Comparing the fibre optic-based thermal monitoring method and the one using MPointS® sensors, in the case where earthworks can be carried out and appropriate financial resources have been committed, the application of the fibre optic-based method for several dozen years long monitoring of the dam will be a potentially more durable and less accident prone solution than the use of MPointS®. Coupled with the no-excavation installation of MPointS® sensors, their application can reduce the cost of the thermal monitoring system and its installation even by a factor of a dozen or so compared with the fibre optic-based temperature measurement system and enable its installation in the situations where for different reasons it is impossible or difficult to carry out earthworks. In consequence, it may be particularly beneficial to be able to apply the MPointS® technology in case of:

a) the need to quickly install a thermal monitoring system, without having to carry out earthworks and to obtain the permits required for earthworks; e.g. in the case of a local, significant intensification of seepage and erosion processes, which causes a concern on the part of experts, particularly at a relatively short section of the damming structure;
b) a planned repair related to the observed seepage and erosion processes and the wish to specify and minimise its extent by exactly identifying these processes; in this case, the damage due to the repair of sensors or even the whole thermal monitoring system does not generate any substantial financial impacts;
c) absence in the long-term of funds for the fibre optic-based system.

Talks with the users of damming structures, particularly small and medium-sized dams, and those that managed dykes, including flood protection ones, often indicated the lack of a cheap and simple method for monitoring a section of the damming structure, up to several hundred meters long, including the leakage zone and the surrounding reference zones. It is especially important in respect of the sections of damming structures the repairs of which can possibly be planned in a matter of several years, but for which it is important and necessary to monitor seepage and erosion processes even now in order to adequately assess their condition and the related safety. In such a case, the Therm3Detect® system is not only consistently suitable for the monitoring of earth dams, but it also fits the methodology for monitoring flood protection dykes described by Radzicki (2014b).

4. A DESCRIPTION OF THE KOZŁOWA GÓRA DAM AND THE OBSERVED SEEPAGE AND EROSION PROCESSES

The Kozłowa Góra Reservoir on the Brynica River is the dam of Upper Silesian Waterworks PLC. It was built in 1935 –1938 to store water for national defence purposes, since a line of fortifications ran along the Brynica River Valley and the reservoir with several weirs was an integral part of them. After the bottom sluice was opened it was possible to flood the river valley downstream of the reservoir to form an anti-tank barrier. However, it has never been used for this purpose. Because of the post-war change of Poland’s borders, the reservoir completely lost its military importance and was used to supply water and protect the land downstream of the reservoir against flood. The water in the reservoir is dammed up by the main dam which 1,300 m long and has its maximum height of 8 m and a side dam which is 2,740 m long. The elevation of the bottom outlet sill is 272.08 m above sea level, while the design elevation of the dam crest is 280.07 m above sea level.

The main earth type dam with a trapezoidal cross-section has been made from local materials. The dam crest over which an asphalt-covered road runs is 8 m wide. The static embankment of the main dam has been made from greatly varied local materials, such as sandstone and limestone debris, sand and dusty sand, with the not systematised distribution of these materials in the dam body. The ground underlying the dam consists of strongly permeable Quaternary formations, medium-grained sands inter-bedded with gravel layers of different thickness locally reaching up to 11m, under which there are impermeable Carboniferous shale layers. Its tight element is an inclined silt core which is 70 cm thick at its base and 18 cm thick at its top. A retaining wall, about 600 m long and connected to the silt core, has been inserted into the ground underlying the dam. The silt core is protected by a 1.60 m trick gravel layer. The upstream slope is protected by 30-35 cm thick setts on a cement mortar, while the downstream slope has been sown with grass. The downstream slope is divided by two benches which are 4.0 m and 2.0 m wide. The water from leaks in the main dam is discharged by a system of ceramic drains in a three-layer gravel sidefill in the downstream toe. The water from the drains flows into an open ditch running at a distance of 6 m from the drain axis. On the upstream side, the crest is protected by a parapet made from prefabricated ferro-concrete elements connected to the tight silt core. A typical dam cross-section is shown in Fig. 3.

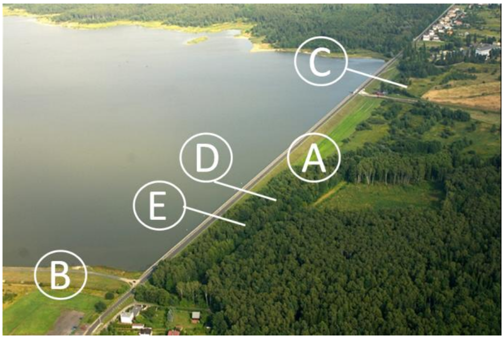

Fig. 2
The Kozłowa Góra Reservoir with its dams (Photo by A.Siudy)
Le réservoir de Kozłowa Góra et ses barrages (Photo par A.Siudy)

(A) Main dam	*(A) Barrage principal*
(B) Side dam	*(B) Barrage latéral*
(C) Piezometric cross-section 1	*(C) Section piézométrique 1*
(D) Piezometric cross-section 6	*(D) Section piézométrique 6*
(E) Piezometric cross-section 7	*(E) Section piézométrique 7*

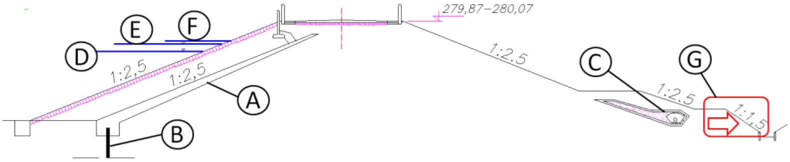

Fig. 3
A typical dam cross-section of Kozłowa Gór Dam
Une coupe typique du barrage de Kozłowa Góra

(A)	Inclined core	*(A)*	*Noyau incliné*
(B)	Diaphragm wall	*(B)*	*Paroi étanche*
(C)	Drains	*(C)*	*Drain*
(D)	Normal water level (278,08 AMSL)	*(D)*	*Niveau normal de retenue (278,08 ASL)*
(E)	Maximum water level (278,58 AMSL)	*(E)*	*Niveau maximal (278,58 ASL)*
(F)	Water level in May 2010 (278.68 AMSL.)	*(F)*	*Niveau du réservoir en mai 2010 (278,68 ASL)*
(G)	Liquefaction zone in May 2010	*(G)*	*Zone de liquéfaction en mai 2010*

In the main dam, 8 piezometric cross-sections were installed: from 0 to 7, each containing 5 to 8 piezometers in which manual water level measurements were carried out every two weeks. Every two weeks, too, the discharges from drain outlets were also measured. At the main dam, 118 surface bench marks were mounted; 105 on the earth body and 13 on the sluice-spillway section. Twice a year their precision levelling was carried out. As indicated by long-term observations of the main dam, one of the zones where strongly intensified seepage and erosion processes were found was the section between and round piezometric cross-sections 6 and 7 (Fig. 2.), with a total length of about 200 m. The benchmarks mounted on the damming structure crest in this zone showed that it subsided by about 2 cm over the last 20 years, intensifying in the period between 1995 and 1998 when it subsided by 1 cm. However, the greatest subsidence in this zone was observed on top of the downstream bench, amounting as a whole to several dozen cm by 2012. Fig. 5B. shows how the bench surface lowered relative to the crest of the one of the drain outlet abutments.

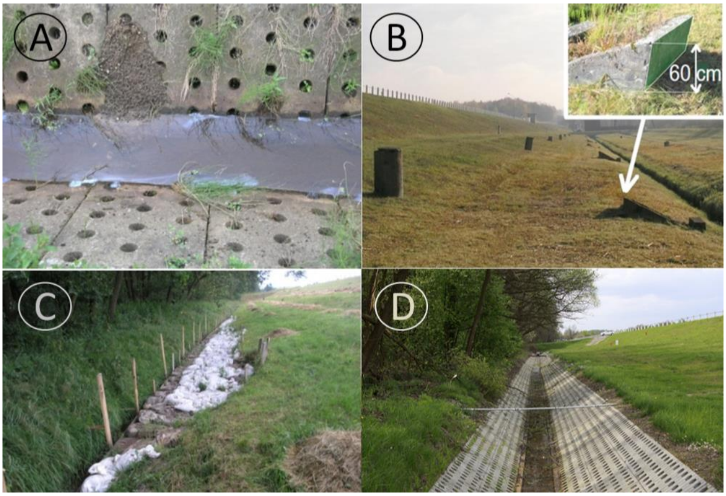

Fig. 4
The downstream toe of the Kozłowa Góra Dam
Le pied aval du barrage de Kozłowa Góra

(A)	Local soil moving out to the ditch (Photo by A.Siudy)	*(A)*	*Lessivage du sol dans la tranchée (photo A.Siudy)*
(B)	Ground subsidence in the downstream toe caused by the ground displacement (Photos by A.Siudy and K.Radzicki)	*(B)*	*Subsidence du sol au pied aval causée par le lessivage du sol (photos A.Siudy et K.Radzicki)*
(C)	Temporary reinforcement of the liquefied toe (Photo by A.Siudy)	*(C)*	*Renforcement temporaire du pied liquéfié (photo A.Siudy)*
(D)	The liquefied zone after repair (Photo by A.Siudy)	*(D)*	*Zone liquéfiée après de la réparation (photo A.Siudy)*

The ground density examination carried out from the bench on the downstream side of the dam showed that, at the depth where the seepage curve occurred in the bench embankment, the ground density status in most holes was determined as loose or very loose in a layer about 0.3 to 0.6 m thick. Underneath the bench the ground was medium dense. In the zone of piezometric cross-sections 6 and 7, losses and cracks were observed in the stone facing of the upstream slope; which could indicate places of intensified seepage into the body. In this zone, relatively large discharges from drainage wells and wet spots on the surface of the downstream bench were observed. Analyses of the variations in the positions of piezometric levels in the main dam, including their time variations relative to water level changes in the reservoir, indicated that probably the silt core had unsealed, particularly in its upper part, in a number of dam cross-sections, including piezometric cross-section 7 (OTKZ 2013).

Because of described problems, from 2006 attempts were made to keep the water level in the reservoir below the elevation of 277.8 m above sea level. Heavy rainfalls which started on 13 May 2010 caused one of the largest floods in Poland’s history and raised the damming level in the reservoir to the elevation of 278.68 m above sea level, i.e. to an excessive maximum water level which is 278.58 m above sea level. This was the highest damming level since 1963. This damming process lasted several days and, subsequently until 30 May the water level was systematically lowered to the operational damming level of 277.8 m above sea level. As a result of the excessive water level in the course of the high water, the height of the position of piezometric surfaces in the dam body significantly rose, with seepage processes intensifying. Combined with a poor condition of the downstream bench, this load caused a liquefaction of its toe the zone of which is shown in Fig. 2. After the high water had passed this place was propped up and reinforced on a temporary basis (Fig. 4C). In 2012, the Upper Silesian Waterworks PLC repaired the damaged bench by restoring its design shape and installing a new drainage pipeline in a gravel sidefill in parallel to the old one (Fig. 4D).

5. DESCRIPTION OF UPGRADED MONITORING SYSTEM AT THE KOZŁOWA GÓRA DAM

The research supervision exercised by the Cracow University of Technology and the cooperation with the Upper Silesian Waterworks PLC in assessments of the condition of dams have a tradition of several dozen years. In continuing this cooperation, with respect to the detected seepage and erosion processes, the Kozłowa Góra Dam was covered by a programme to install advanced, innovative monitoring systems, particularly for thermal monitoring of seepage and erosion processes, in order to identify their dynamics and behaviour. The long-term, rich experiences of the Cracow University of Technology in the development of thermal monitoring methods were drawn upon, connecting the results of own Polish research and development programmes and those carried out in cooperation with French research centres.

On the occasion of the abovementioned reconstruction of the liquefied downstream toe and the simultaneous drain replacement in the zone of piezometric cross-sections 6 and 7, a thermometric fibre optic cable was mounted on the upstream side of new drains within the framework of the cooperation of the Cracow University of Technology with the French companies EDF and GeophyConsult. In the present year 2014, the Upper Silesian Waterworks PLC plans to buy a DTS unit to enable measurements with the installed optic fibre cable.

In addition, in 2014, the Therm3Detect® system described above was installed on the dam in the form of MPointS® sensors mounted between two piezometric cross-sections 6 and 7 and around piezometric cross-section 1 in the downstream toe on the upstream side of the drains. Moreover, MCableS® were mounted in all the piezometers of these piezometric cross-sections. In order to ensure an detail analysis of seepage and erosion processes, sensors were also installed for local measurements of thermal loads all along the dam and the vertical temperature profiles in the reservoir in the three abovementioned piezometric cross-sections, too. The system was also complemented with automatic pressure measurements and a weather station carrying out basic measurements of weather parameters.

The installed system was designed simultaneously as a field laboratory serving to develop and test methods for thermal monitoring of seepage and erosion processes. Numerous extended sequences of MPointS® sensors were mounted at different depths and in different measurement sequences spaced along the dam. One of the important installations mounted for the purposes of planned tests was also the one for simulating an artificial leak, situated close to piezometric cross-section 1, enabling the precise control of soil moisture content and seepage velocity in a selected zone of the downstream side of the damming structure.

Fig. 5 shows an example of some temperature measurements carried out with MPointS® sensors along the dam, installed in the bench close to the upstream side of drains. Fig. 6 shows an example of the measurements carried out by MCableS® sensors in the piezometers located on the downstream edge of the dam crest in cross-sections 6, 7 and 1.

The installation of a system for thermal monitoring of seepage and erosion processes, with its features resembling the one described above, is underway on a flood protection dyke in Poland, along an about 200 m long section, where in the course of high water several zones of intensified seepage and erosion processes, several to a dozen or so metres wide, were observed. In the course of the high water, on a provisional basis, they were propped up with sand bags. The dyke section in question waits for a planned repair; however, because of the limited budget of the unit which manages the dyke, this will not take place soon.

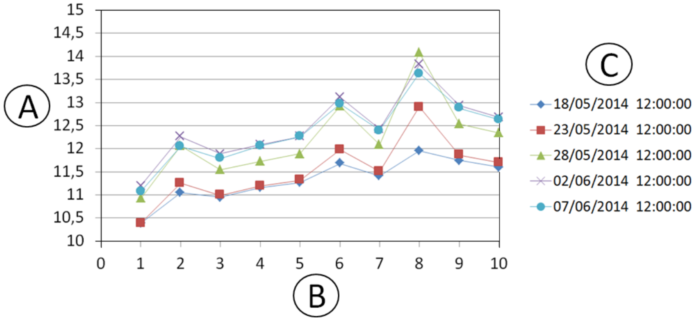

Fig. 5
An example of some measurements carried out by MPoints® sensors placed along the dam on top of its downstream bench
Exemple de mesures effectuées par des capteurs MPoints® placés le long du barrage sur le dessus du banc aval

(A) Temperature ºC	*(A) Température ºC*
(B) Distance in meters	*(B) Distance en mètres*
(C) Measurement time	*(C) Temps de mesure*

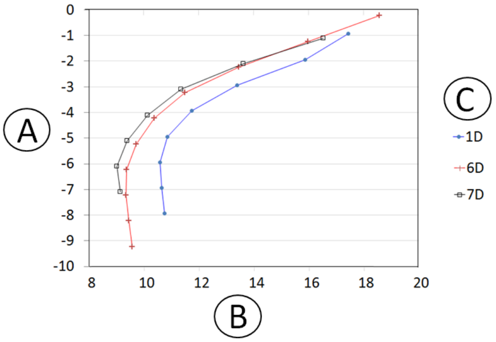

Fig. 6
Examples of measurements carried out by MCables® sensors in the piezometers located on the downstream edge of the dam crest in cross-sections 6, 7 and 1, 1st June at noon
Exemples de mesures effectuées le 1er juin à midi par des capteurs MPoints® dans les piézomètres situés sur le bord aval de la crête du barrage dans les sections 6, 7 et 1

(A) Depth in meters	*(A) Profondeur en mètres*
(B) Temperature ºC	*(B) Température ºC*
(C) Piezometer number	*(C) Numéro de piézomètre*

CONCLUSIONS

The innovative thermal monitoring system presented in the article was designed to enable a more widespread application of the thermal monitoring method to detect and analyse seepage and erosion processes in damming structures, such as dams, channel embankments or flood protection dykes. This system is particularly suitable for application at existing damming structures. The key advantages of this system include temperature sensors mounted without an excavation and the possibility of carrying out both continuous measurements all along the damming structure and vertical temperature profile measurements at cross-sections of the damming structure.

The applied solutions can significantly reduce the costs and expedite and simplify the installation of the thermal monitoring system. These features of the measurement system seem to be of key importance for disseminating the thermal monitoring method. The system described here can be particularly useful for an assessment of the course and dynamics of seepage and erosion processes in order to exactly plan the scope and time of a repair or, when waiting for a planned repair, in order to exactly assess the condition of the damming structure. It may be one of the important measuring tools in the thermal monitoring method, apart from the method for fibre optic-based temperature measurements, giving engineers more freedom in designing and implementing systems for thermal monitoring of damming structures. Described system was successfully installed e.g. on the Kozłowa Góra Dam, where a number of important, intensified seepage and erosion processes were observed, in order to explore them in depth.

The main purpose of this article was to present a new sensor solution. It should be borne in mind that correctly located and implemented temperature measurements are one of the two pillars of the thermal monitoring method. The other pillar is an appropriate data analysis using relevant methods and models which make it possible to read out the information contained in the thermal signal measured. In the case of the Kozłowa Góra Dam, a detailed expert analysis of seepage and erosion processes by the thermal monitoring method – combined, too, with the analysis of data from sensor types other than temperature sensors – is underway and will be presented in subsequent publications.

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SUMMARY

The erosion processes are some of the major threats for the safety of earth dams, channel embankments and flood protection dykes. The identification of their spatial pattern and their dynamics is of key importance for a correct safety assessment of the damming structure and for optimizing the necessary repairs. The thermal monitoring method is a recognized and one of the recommended methods for detection and analysis of these processes. One of the main elements ensuring its effectiveness is the distributed temperature sensing by means of fibre optic cables, enabling the continuous monitoring of seepage and erosion processes all along a dam or dyke. However, for existing damming structures it may be difficult and relatively expensive to apply this method, particularly in the case of short measurement sections. It can result in the limited extent of common use of thermal monitoring method.

This article presents the assumptions and an example of the application of a 3D system for thermal monitoring of damming structures, where an innovative, no-excavation solution, enabling cheap, quasi-continuous temperature measurements all along the damming structure, plays a special role. It is complemented with vertical temperature measurement profiles designed to detailed analysis of intensified erosion processes at cross-sections of the dam. This system was used, inter alia, at the main dam of the Kozłowa Góra Reservoir, where intensified seepage and erosion processes were found at a number of places, particularly when the 2010 flood wave occurred there, including a local liquefaction of the downstream toe. This reservoir is one of the key reservoirs in the system of water supplies for Śląskie Province and for flood protection in Poland. At the same time, the installation was designed as an advanced field laboratory serving to develop thermal monitoring methods, particularly with a view to their application on an existing damming structure. Among others, a system to simulate leakage was there installed. This article describes the Kozłowa Góra Dam and the seepage and erosion problems observed there and it presents basic information concerning the thermal monitoring method. It also describes the innovative thermal monitoring system applied there and presents the first measurements carried out in it.

RÉSUMÉ

Les processus d'érosion font partie des principales menaces pour la sécurité des barrages en terre, digues de canaux et digues de protection contre les inondations. La caractérisation de leurs propriétés spatiales et de leur dynamique est d'une importance clé pour l’évaluation de la sécurité de la structure de retenue et pour optimiser les réparations nécessaires. La méthode reconnue d’auscultation thermique est l'une des méthodes recommandées pour

la détection et l'analyse de ces processus. L'un des principaux éléments assurant son efficacité est une mesure répartie de température par fibres optiques, permettant la surveillance continue des processus d'infiltration et d'érosion le long d'un barrage ou d'une digue. Cependant, pour les ouvrages d'endiguement existants, il peut être difficile et relativement onéreux d'appliquer ce procédé, en particulier dans le cas de sections des mesures relativement courtes. Cela peut entraîner des limitations dans l'universalité de son application.

Cet article présente les principes et un exemple de l'application d'un système 3D de surveillance par auscultation thermique des ouvrages de rétention des eaux, dans lequel une solution innovante, sans excavation, permettant à bas prix des mesures quasi-continues de température tout au long de l'ouvrage joue un rôle particulier. Il est complété par des profils verticaux de mesure de température destinés à l'analyse détaillée des processus d'érosion dans des coupes du barrage. Ce système a été utilisé, entre autres, au barrage de Kozłowa Góra, où des processus intensifs d'infiltration et d'érosion ont été identifiés à plusieurs endroits, en particulier lorsque de la crue 2010 qui a été marquée par une liquéfaction locale du pied aval du barrage. Ce réservoir est l'un des principaux réservoirs du système d'approvisionnement en eau de la province de Silésie et l'un des ouvrages de protection contre les inondations en Pologne. Dans le même temps, ce système a été conçu comme laboratoire de terrain servant à développer des méthodes d'auscultation thermique, notamment en vue de leur application sur une des barrages existants. Entre autres, on y a installé un système de simulation des fuites. Cet article décrit le barrage de Kozłowa Góra et les problèmes d'infiltration et d'érosion observés et présente les principales informations concernant la méthode de surveillance thermique. Il décrit également le système innovant de surveillance thermique appliqué et présente les premières mesures effectuées avec celui-ci.