



# Seepage monitoring and leaks detection along an earth dam with a multi-sensor thermal-active system

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## Abstract

Thermal investigation using linear sensors installed in the ground is currently one of the most effective methods for analyzing seepage processes in the bodies of earth dams or dikes and their subsoil, including leaks detection. However, linear, fiber-optic temperature sensors present several limitations when applied to existing structures, including installation difficulties and substantial costs. To enhance the applicability of the thermal method for studying subsurface water flow, a novel Multi-Point Thermal-Active Monitoring method has been devised. The approach consists of installing, through hammering, thermal-active sensors side-by-side in the ground, at the same depth in a single line thereby achieving quasi-continuous measurements along the structure. Small openings from sensor installation are secured with bentonite and do not pose a threat to the structure. Each sensor is equipped with a micro-heater, which enables the use of the thermo-active method to determine in-situ seepage velocity. This article describes this method and its initial application in 2014 on one of the Polish earth dams. This application enabled the detection of two leakage zones and the monitoring of their flow velocities, leading to the successful validation of the described technology.

**Keywords** Multi point thermal-active seepage monitoring · Leakage detection · Linear sensors · Coupled heat and water transport · Earth dam

## Introduction

Acquiring accurate information concerning the magnitude and course of intense seepage pathways, encompassing leaks, and particularly the value of seepage velocity, as well as their progression dynamics, forms the basis for a reliable assessment of the state and safety of earth-damming structures such as dams or levees (Deneale et al. 2019; ICOLD 2017). However, typical methods that have been used for decades to analyse seepage processes do not allow for continuous monitoring along these structures, nor often early detection of leaks. The introduction of the geophysical thermal monitoring method, utilizing a fiber-optic temperature sensor, has brought significant qualitative improvement in

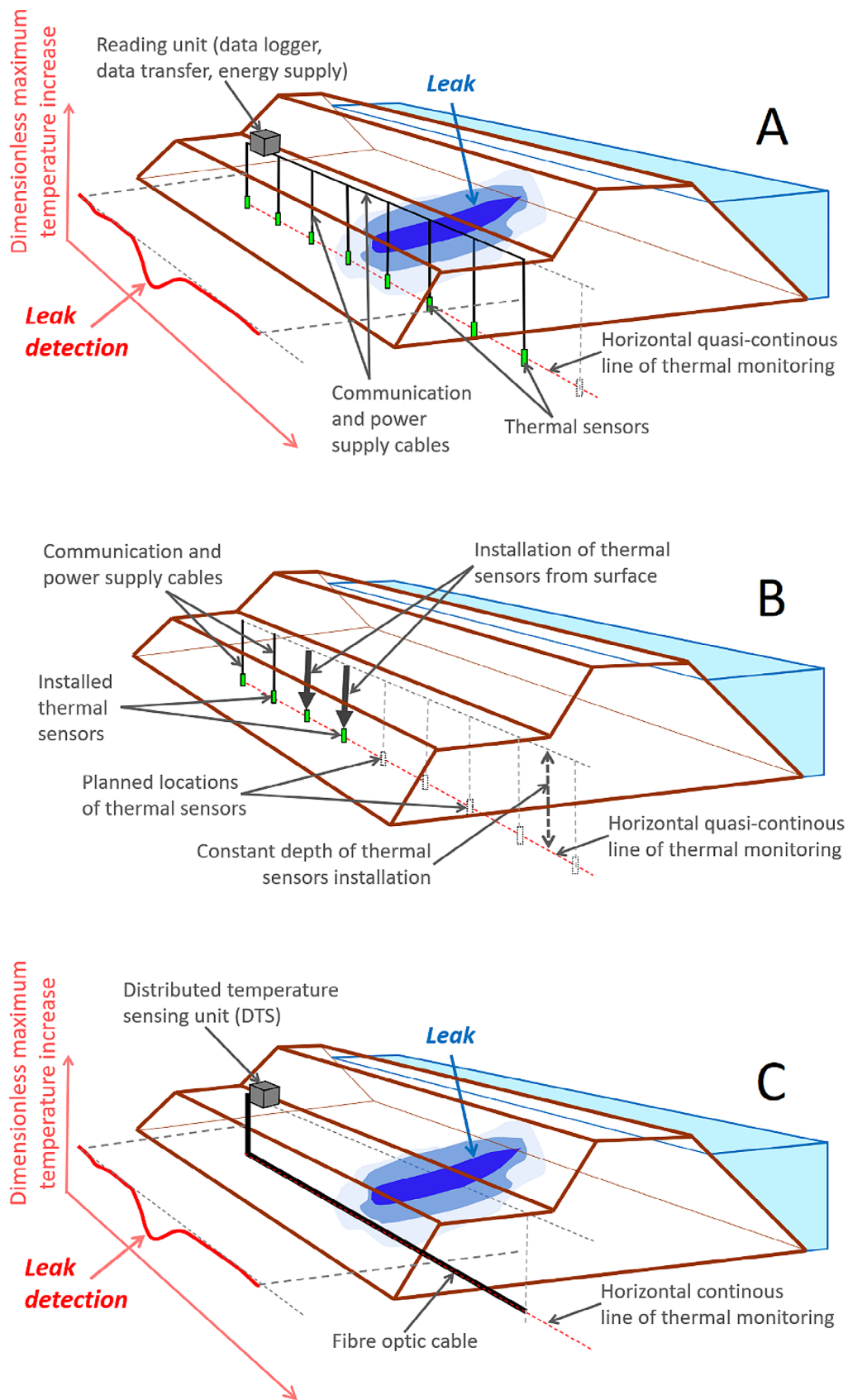
the accuracy and reliability of monitoring these processes (Fry 2012; ICOLD 2017) at the onset of the new millennium. In particular, this method allows for continuous monitoring of seepage processes along the entire length of the structure and in-situ measurement of seepage velocity if, additionally, an thermal-active method involving sensor heating is applied (Aufleger and Strohbl 2000, Courivaud et al. 2011; Perzlmaier et al. 2007). Fiber-optic cables are installed at a specific depth within the structure and/or subsoil along a structure, as schematically shown in Fig. 1C. It is connected to Distributed Temperature Sensing (DTS) unit, which includes a laser for emitting light pulses and a light spectrum analyzer, among other components. This device automatically enables temperature measurement along the entire length of the fiber-optic cable by comparing relevant parameters of the spectrum of the transmitted laser pulse and the spectrum of back-scattered light, even up to several tens of kilometers (Tyler et al. 2009).

The inaugural application of temperature measurement for the investigation of seepage processes in earth dams was documented in the late 1960s (Kappelmeyer 1957). In the 1980s, they began to be more frequently employed.

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**Fig. 1** Schema of the Multi Point Thermal-Active Monitoring system (A), and its installation (B), as well as the fibre-optic based thermal monitoring system (C) (adapted from Radzicki et al.2021)

However, at that time, methods directly derived from hydrogeology and geothermics were used (Merkler et al. 1985, Merkler et al. 1989). In the 1990s, the thermal method was developed with the aim of applying it to earth dams (Dornstädter 1997, Dornstädter and Huppert 1998; Johansson 1991). In the initial years of the new millennium, the first linear fibre optic sensors were deployed for natural temperature measurements (Aufleger et al. 2000; Johansson 2000, Johansson et al 2023). Several years later, in the monitoring of leaks in dams and canal dikes, fiber-optics, combined with the thermal-active investigation method involving their heating, begins to be employed (Aufleger et al. 2005; Fry 2005; Perzlmaier 2006). The heating of a fiber-optic cable is performed using the method of electrical resistance, achieved by passing current through a steel wire which constitutes one of the cable's armour components. The linear monitoring of earth-damming structures utilizing fiber-optics has been thoroughly validated in small-scale tests (Cao et al. 2019; Cheng et al. 2021; Ghafoori et al. 2020; Yan et al. 2015). Tests conducted in field laboratories, where simulations of leaks and internal erosion were replicated at actual scale were particularly important. These large-scale evaluations were performed at various locations, including an experimental basin in Aix-en-Provence, France (Artieres et al. 2007; Vedrenne et al. 2009) and the IjkDijk test sites in the Netherlands (Artieres et al. 2007). Over the last two decades, the thermal method has been applied to investigate several hundred damming structures worldwide. Moreover, it is used in numerous structural health monitoring systems of these structures (Beck et al. 2015; Cola et al. 2021; Dornstädter and Heinemann 2012; Johansson and Watley 2004; Johansson et al. 2015 and 2023). These multiple applications of this method, along with the results of the aforementioned tests, have led to the endorsement of this method by, among others, the most reputable global institution in the field of hydraulic engineering, the Int. Commission on Large Dams." In its bulletin (ICOLD 2017), it was asserted that "Many less direct means of detecting seepage are now available. The most promising is temperature measurement, which can be used to infer localized flow." Additionally, the bulletin highlighted that "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."

However, fiber-optic linear sensors are a type of sensor that are especially suited to installations during the construction of new earth dams or levees, over which such cables can be easily and inexpensively laid in the most optimal locations. Whereas, the installation of these sensors on existing dam structures poses significant limitations. In particular, there is a relatively high installation cost for short sections of the existing structures, and a risk of disrupting

soil continuity when using cable plowing or laying cables in ditches, and consequently creating potential seepage and erosion pathways (Courivaud et al. 2011; Radzicki et al. 2021). Moreover, active thermal measurements with a fibre-optic cable consume for a heating a large amount of energy, up to 15 W per metre of fibre-optic cable, for seepage velocity determination (Beck et al. 2010). Thus, permanent monitoring system with fibre-optic cable must be usually connected to a power grid or generator sets must be used. However, damming earth structures, particularly levees, are often located far from power grids. In addition, the installation depth of fibre-optic cables is limited to a few metres, which impedes the monitoring of deeper zones of the structure, especially the subsoil (Radzicki et al. 2021). The aforementioned facts are exemplified by the summary provided by Johansson (2023), detailing the quantity of fiber-optic installations for thermal examination of seepage processes implemented in Sweden from 1998 to 2023. During this period, fiber-optics were deployed on 85 earth dams and 5 tailing dams, covering a total length that exceeds 140 km. It is emphasized, however, that these installations were predominantly carried out in newly constructed or renovated structures. More than half of the installations took place between 2004 and 2009, concurrent with an extensive dam safety renovation program conducted by hydropower companies in Sweden.

To enhance the applicability of the thermal method to investigate existing dams, we have devised a new approach called Multi Point Thermal-Active Monitoring. It employs a quasi-continuous monitoring array of thermal-active sensors, thereby effectively addressing the aforementioned limitations of fiber-optic sensors. This novel technology enables the rapid installation of sensors in existing earthen structures at significantly greater depths, while avoiding the creation of potential seepage and erosion pathways, unlike fiber-optic cable installations. Furthermore, compared to fiber-optic cable, it also consumes several times less energy during thermal-active in-situ seepage velocity measurements. Thus, it represents an innovative solution that facilitates a much easier, faster, safer, and consequently more frequent application of thermal methods for monitoring leaks and erosion processes in existing damming structures than fiber-optic cable.

A description of the thermal methods used for investigating seepage processes, with particular emphasis on the Multi Point Thermal-Active method is presented in the next chapter of this article. The article is devoted to describing the pioneering application of this method. The method was used to investigate seepage processes at Kozłowa Góra dam in 2014. This endeavour also marked the first ever implementation of the thermal monitoring method in Poland at all for the seepage investigation in earth-damming structures.

First, the characteristics of the Kozłowa Góra dam and the intensive seepage and erosion processes identified there by inspection are presented. The following part of the article describes the Multi Point Thermal-Active monitoring system installed on this dam. Subsequently, the results of implementing this system are presented, initially for the measurement of natural soil temperature and later for thermal-active measurements. Simultaneously, a comprehensive analysis of these findings is provided along with discussion. The last chapter summarizes crucial findings derived from the study.

## Method

### Coupled heat and water transport in soil

The thermal analysis of water flow in soil relies on the interconnected dynamics between heat and fluid transport phenomena. When there is no water flow, heat conduction is the dominant process, but it occurs relatively slowly. However, even a variation in soil moisture content can have a substantial impact on local thermal front velocities. Furthermore, with the occurrence of water flow, such as seepage including leaks, heat is transported along with the flowing water. This phenomenon, known as advection, generates a significantly higher heat flow compared to conduction. The magnitude of heat flow is directly proportional to the velocity of fluid flow (Bear 1972; Johansson 1991). The temperature distribution over time and space within the soil, including a dam body and its subsoil is described by a parabolic energy balance equation, which can be expressed as follows (Bear 1972; Johansson 1991):

$$C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i} \left( \lambda \frac{\partial T}{\partial x_i} - C_w T q_i - Q_{disp} \right) \quad (1)$$

where:

$C$  = volumetric heat capacity of two-phase porous system of soil and water, ( $\text{Jm}^{-3}\text{K}^{-1}$ )

$C_w$  = volumetric heat capacity of water, ( $\text{Jm}^{-3}\text{K}^{-1}$ )

$Q_{disp}$  = energy flux due to mechanical and thermal dispersion, ( $\text{Jm}^{-2}\text{s}^{-1}$ )

$q_i$  = seepage velocity (Darcy flow), ( $\text{ms}^{-1}$ )

$T$  = temperature, ( $^{\circ}\text{C}$ )

$\lambda$  = thermal conductivity of two-phase porous system of soil and water, ( $\text{Wm}^{-1}\text{K}^{-1}$ )

The energy flux comprises heat conduction in the solid phase and water (the first term on the right of the Eq. 1), heat advection with the average seepage velocity (the second term on the right), and dispersion resulting from the variability in the local water flow velocities (the third term

on the right). Internal erosion processes, alter soil properties, particularly local porosity, thereby influencing the magnitudes and orientations of water flow vectors within the seepage zone. As a result, erosion process causes distinct disruptions in the thermal-hydraulic field, thereby enabling the identification of this process through thermal methods (Beguin 2011; ICOLD 2017; Radzicki and Bonelli 2010, 2012a). Therefore, the utilization of thermal methods enables the detection and analysis of erosion and seepage processes, including leaks.

### Multi point thermal-active monitoring method

The pivotal component of the Multi Point Thermal-Active Monitoring system is an array of thermal-active sensors. It is installed by inserting successive thermal-active sensors into the soil in series, without trenches. The sensors can be installed one next to the other to create quasi-continuous horizontal line of sensors as illustrated in the schema in Fig. 1B, for monitoring leaks along the entire length of a damming structure, such as an earth dam or levee (Fig. 1A).

However, the thermal-active sensors can also be arranged in various spatial configurations including two or more measurement profiles, forming a quasi-two-dimensional measurement plane. This configuration can be used for monitoring of both, the body and the subsoil of the structure (Radzicki et al. 2021). The spatial distribution resolution of sensors is individually adjusted for each structure, taking into account the analysis of soil parameters and the potential development of seepage and erosion processes. This approach allows for the optimization of system costs while maintaining quasi-continuity of measurements in space. Multipoint thermal-active sensors are installed from the surface, typically inside the lower bench of the dam or inside its downstream toe. This location enables the detection of leaks from the entire cross-section of the dam which extends towards its downstream part, and facilitating the identification of early signs of erosion processes. These processes often initiate from the downstream toe zone and propagate by the body or through subsoil towards the reservoir (ICOLD 2017). Each thermal sensor is integrated with a micro-heating device, enabling both passive investigation, which involves measuring natural ground temperatures, and active measurements, achieved through the heating of the sensor (Radzicki et al. 2021). Sensor accuracy is 0,1  $^{\circ}\text{C}$ .

Interpreting the natural temperature measurements usually necessitates the utilization of advanced sophisticated signal analysis models and long-term measurements. Moreover, the outcomes of this method can be significantly influenced by the fluctuation of external thermal loads and the specific time of the year during which the measurements are conducted (Artiere et al. 2007, Beck et al. 2015). The

challenges of analysing natural soil temperature measurements are extensively discussed on the example of Kozłowa Gora Dam in the Chap. 4.

The active method, unlike the passive approach, requires only a few dozen minutes for each investigation and is not affected by external thermal condition variability. It involves the integration of a heat generator with an electrical or electronic temperature sensor. The primary focus lies in analysing the temperature rise curve of the heated sensor with an integrated micro-heating device, which exhibits variations dependent on the soil's moisture content and water flow rates. As the soil moisture or seepage rate escalates, the cooling effect exerted on the sensor becomes more prominent, resulting in a diminished temperature rise during the heating process (Perzmaier et al. 2007). Thermal-active sensors of Multi Point Thermal-Active Monitoring system are calibrated to enable in-situ investigations of seepage velocity with heating mode. The temperature curves of thermal-active sensors heated with an integrated micro-heating device are recorded in the laboratory during heating and cooling cycles at different seepage velocities. Calibration is performed using a seepage chamber to control the seepage velocity. Subsequently, the field temperatures measured during the heating investigation are compared to this registered database of curves of thermal-active measurements to determine the seepage velocity (Radzicki et al. 2021). The possibility of in-situ seepage velocity measurement is one of the key advantages of the active-thermal method. This parameter represents the most crucial information characterizing seepage, simultaneously being highly unequivocal, reliable, and immediately comprehensible to any hydraulic works engineer. When detecting intensified seepage zones within these leaks, the results of the active-thermal

investigation do not necessitate additional advanced statistical analysis and expert interpretation, unlike the passive-thermal method application.

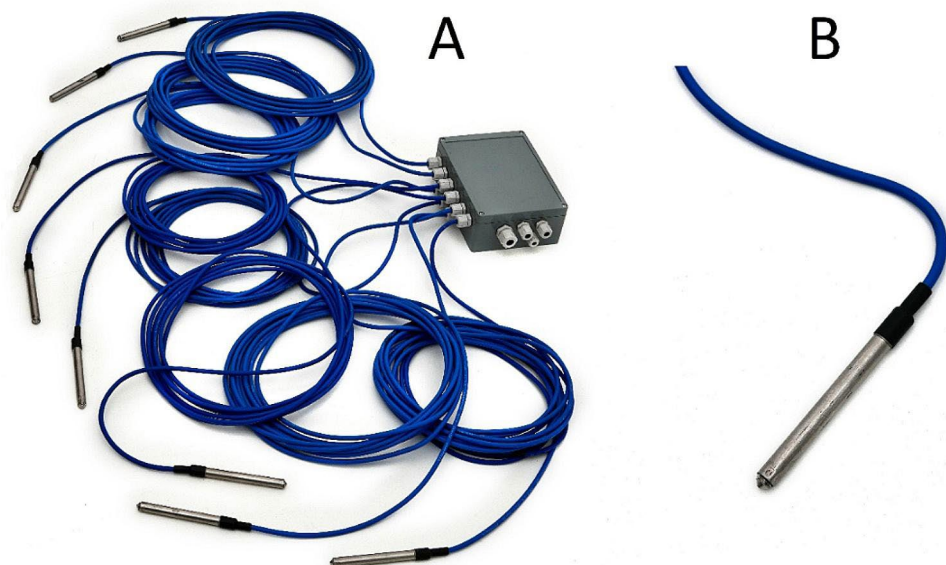
Thermal-active sensors can be installed from the surface to depths of several meters utilizing lightweight drills and mechanical hammers devoid without using heavy vehicle. Following sensor installation, the orifice is packed with bentonite to avoid uncontrolled water ingress and to prevent the progression of leaks and erosion. Bentonite sealing is a well-established and highly effective solution for orifice sealing. It is commonly applied for example in the sealing of abandoned wells. (Corina et al. 2022). Consequently, the installation of sensors neither causes discontinuities nor creates privileged seepage pathways, thereby mitigating the risk of soil erosion (Radzicki et al. 2021). For the purpose of rapid and facile assembly of the Multi Point Thermal-Active Monitoring system, as well as to enable easy scalability of its size to the monitored section's length, universal measurement module has been developed. The module comprises eight thermal-active sensors connected by cables to a single junction box, enabling power supply and sensor control. Figure 2 depicts an image of such a module and a close-up of an individual sensor. Depending on the required number of sensors in the system, an appropriate quantity of measurement modules is mounted.

## Kozłowa gora earth dam and the problem of leaks and erosion

### Kozłowa gora dam

The Kozłowa Gora earth dam, situated on the Brynica River in the Silesian Voivodeship of Poland, close to Katowice

**Fig. 2** Universal module of Multi Point Thermal-Active Monitoring system module (A) and close-up photo of one of the sensors (B)

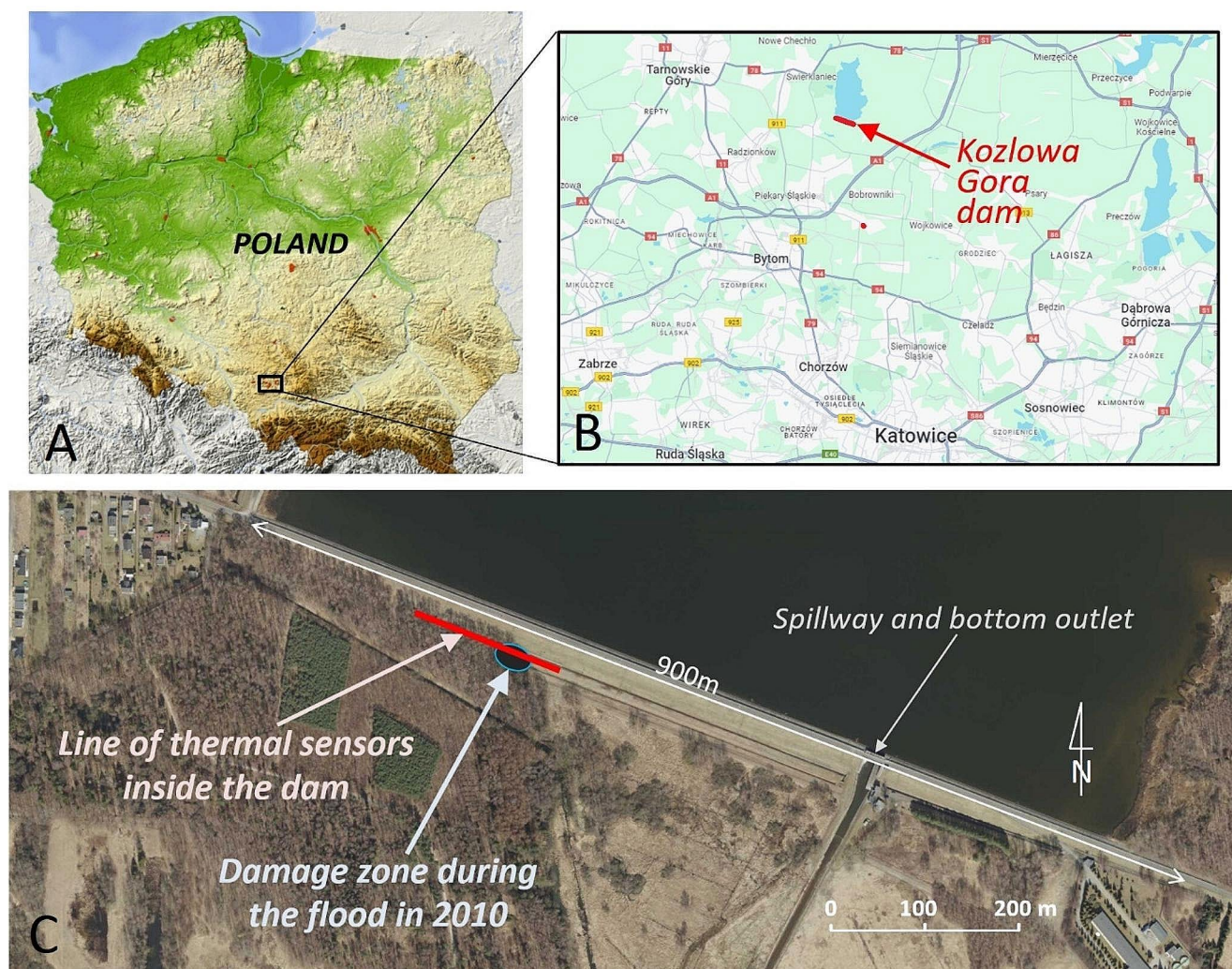




town, was constructed between 1933 and 1939 with the original intention of serving as a reservoir to flood the downstream river valley for military purposes. However, due to the alteration of Poland's borders after World War II, the dam lost its military significance and has since been utilized for water supply and flood protection. An aerial view of the dam is depicted in Fig. 3. The dam, stretching 1300 m in length and reaching a height of 8 m, features an 8-meter-wide crest that accommodates an asphalt-covered road. Figure 4 illustrates a typical cross-section of the dam. The construction of the dam employed a different range of local materials, including sandstone, limestone debris, sand, and dusty sand, with no systematised distribution of them within the dam body.

The dam body incorporates an inclined silt core located in the upstream part of the body. The core is 70 cm thick at the base and 18 cm thick at the top. The core is protected by a 1.60 m thick gravel layer. Below the lower part of the

core, a wooden sheet piling is installed in the subsoil. The upstream slope is protected by a 30–35 cm pavement on a cement mortar (Fig. 5), while the downstream slope (Fig. 8) is grassed and divided by two benches, measuring 4.0 m and 2.0 m in width respectively. At the downstream toe of the dam, a gravel drainage system with a perforated drainage pipe in the bottom is present. Water from the drainage is discharged through transverse pipes into a ditch situated alongside the dam. The subsoil beneath the dam is composed of permeable Quaternary formations, consisting of medium-grained sands interspersed with layers of gravel that can reach a thickness of up to 11 m in certain areas. These formations are underlain by impermeable layers of Carboniferous shale.



**Fig. 3** A) General location of the Kozłowa Góra dam; B) Detailed location of the dam (map: [www.google.pl/maps](http://www.google.pl/maps)); C) Aerial view of the dam and location of the linear monitoring system with the thermal-active sensors (map: [www.google.pl/maps](http://www.google.pl/maps))



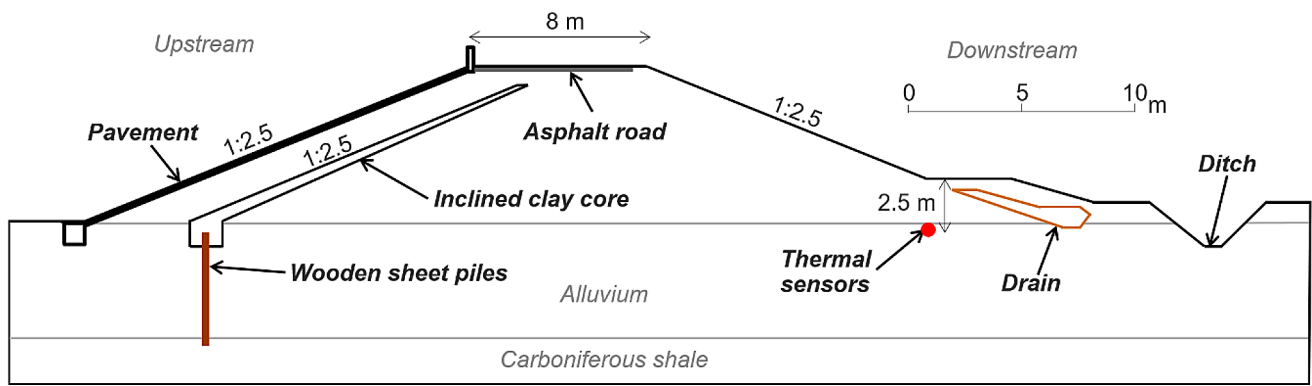


Fig. 4 Placement of the thermal-active sensors in a standard cross-section of the Kozłowa Góra Dam

Fig. 5 Crest and water-side part of the Kozłowa Góra dam



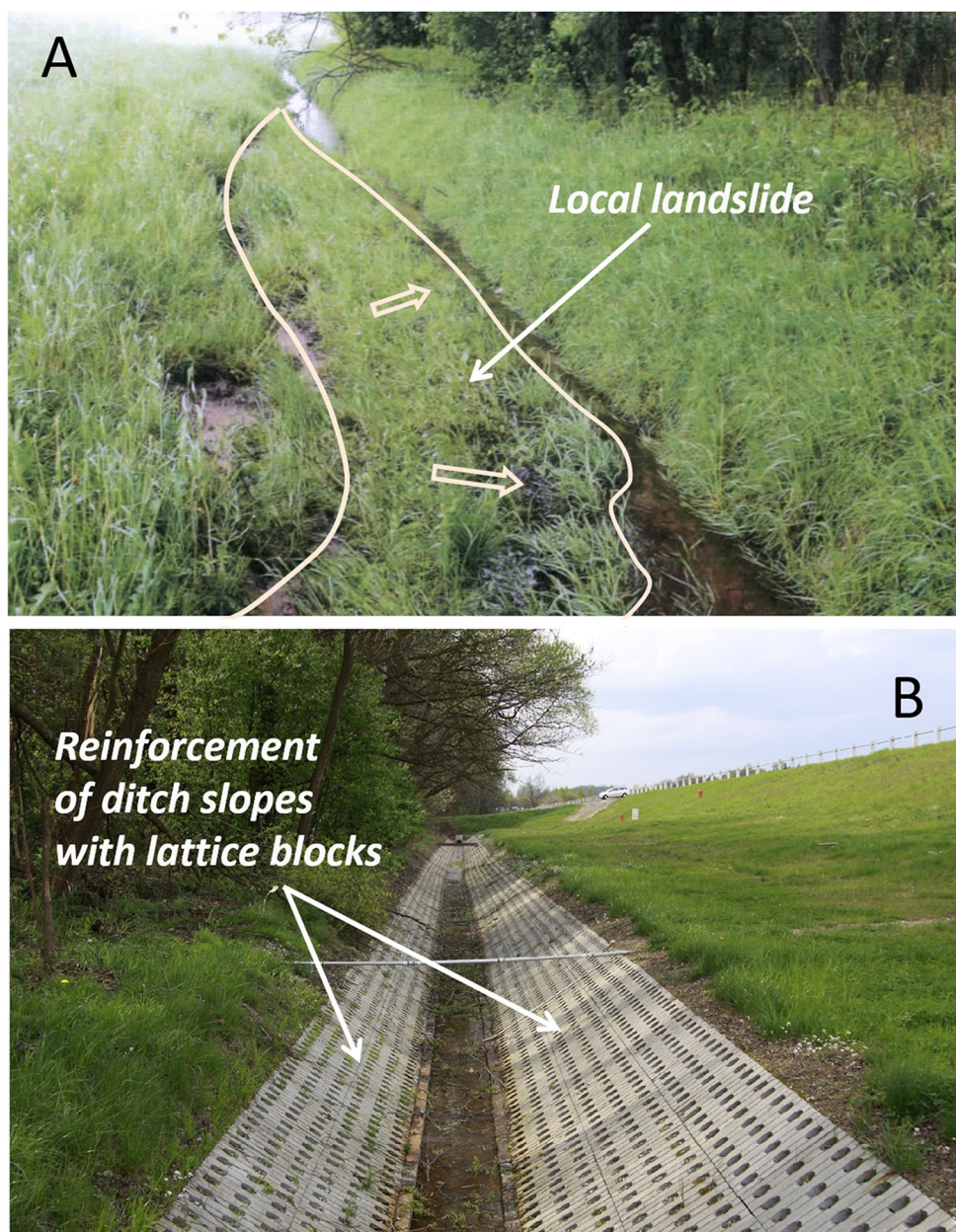
Fig. 6 Soil erosion observed in the ditch of the dam

### Intensive seepages and internal erosion problems

Long-term observations of the dam identified a zone of several dozen metres of intensified seepage and erosion processes marked in Fig. 3. Benchmarks installed on the crest of the dam in that area indicate a subsidence of approximately 2 cm over the past 20 years. Nevertheless, the most significant subsidence within the zone was observed on the downstream bench, reaching a total of several dozen cm by 2012. Relatively large drainage well outflows, wet spots on the surface of the downstream bench, and washing out of soil particles into the ditch (Fig. 6) were also identified in that zone. Geotechnical investigation of the ground density conducted from the downstream side bench of the dam revealed that at the depth where the seepage curve occurred, the ground exhibited loose or very loose characteristics in a layer ranging from approximately 0.3 to 0.6 m. The underlying ground below this layer was found to be of medium density. During one of the largest floods recorded in Poland in 2010, the water level in the reservoir remained close to the



**Fig. 7** Zone of a local landslide during the 2010 flood (A) and its transformation after renovation in 2012 (B) along the previously described section of the dam threatened by increased seepage and internal erosion



maximum level for several days. At that time, seepage processes intensified in the discussed zone, which even led to local landslide of the dam's landside toe. Figure 7A depicts the zone with damage, whereas Fig. 7B illustrates it after its restoration in 2016.

### Multi point thermal-active monitoring system

Initially, a fiber-optic cable was planned to be installed erosion. However, in the landside body of the dam, the position of the seepage line was so high that the installation of the cable for which, as mentioned earlier, the excavation of a trench or the use of a cable plow is necessary, posed a risk of locally intensified erosional processes. On the other

hand, deploying the cable installation under the protection of a wall made of sheet piles would entail substantial additional costs. These challenges prompted the conception of the Multi Point Thermal-Active Monitoring system in 2012. Following financial support from the Polish National Centre for Research and Development, this technology was developed. As a result 140 thermal-active sensors were installed every 1 m, as shown in the diagram in Fig. 1, inside the landside bench in one line on a 139 m section (Fig. 8) along the Kozłowa Góra dam in 2014. The black lines in Fig. 8 were added to improve clarity in illustrating the shape of the dam and pinpointing its edges in the photograph.

Due to a fact that it was a pilot installation for the described technology, above each thermal-active sensor located at a





**Fig. 8** Crest and land-side part of the Kozłowa Góra dam including location of thermal sensors in its landside toe

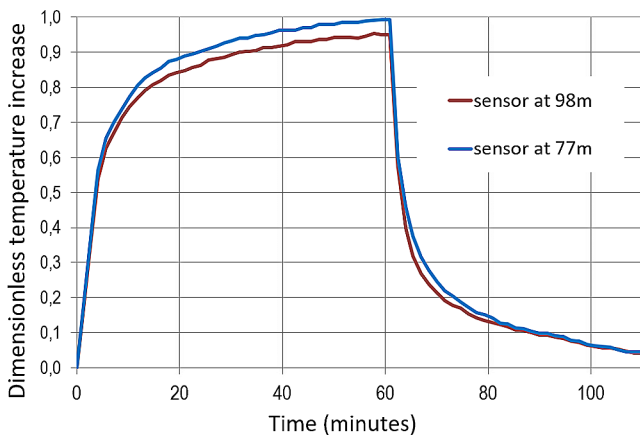
depth of 2.5 m, an additional passive sensor was installed at a depth of 25 cm below the ground surface to measure the natural ground temperature. The purpose of this measure was to more accurately monitor temperatures around the thermal-active sensors. Assembly of all sensors along a 139-meter section of the dam, along with the remaining instrumentation of the monitoring system enabling power supply, measurement control, and remote data transmission, was completed in just under two days. Given that this was the initial pilot installation of the technology and considering the possibility of scaling the installation team in proportion to the length of the installation section, it can be inferred that this technology is easily applicable.

## Results and discussion

Thermal investigations of seepage processes at the Kozłowa Góra dam were conducted over five consecutive weeks in November and December 2014. The daily measurement protocol comprised four cycles of investigations performed, at every 6 h. During each such investigation, firstly, all temperature sensors, both passive and active ones, located at depths of 0.25 and 2.5 m, respectively, recorded the natural ground temperature. Subsequently, all 140 thermal-active

sensors positioned along the dam at depth of 2.5 m were uniformly heated for one hour immediately following the initial measurements of the natural soil temperature. After that, the heating was discontinued, allowing the sensors to self-cool to the natural soil temperature. An illustration of such thermal-active measurements for two sensors located at 77 m and 98 m along the monitored section, taken on November 12, is presented in Fig. 9. Where the first profile is characteristic for lower seepage velocities within the examined section of the dam, and the second one corresponds to the highest measured seepage velocity observed throughout the entire five weeks of the study. The seepage velocities at both of these points were determined by a method that is elucidated in the Chap. 2.2. The parameter of the vertical axis in Fig. 9 represents a dimensionless temperature increment. It is expressed (Eq. 2) as the ratio of the difference between the measured temperature  $T_i$  at a given moment and the temperature of the first measurement  $T_0$  in a given investigation, to the maximum temperature  $T_{max}$  increment for a single sensor due to heating over the entire five-week measurement cycle, and taking into account all thermal sensors from the monitored Sect.

$$\Delta T_i = \frac{T_i - T_0}{T_{max}} \quad (2)$$

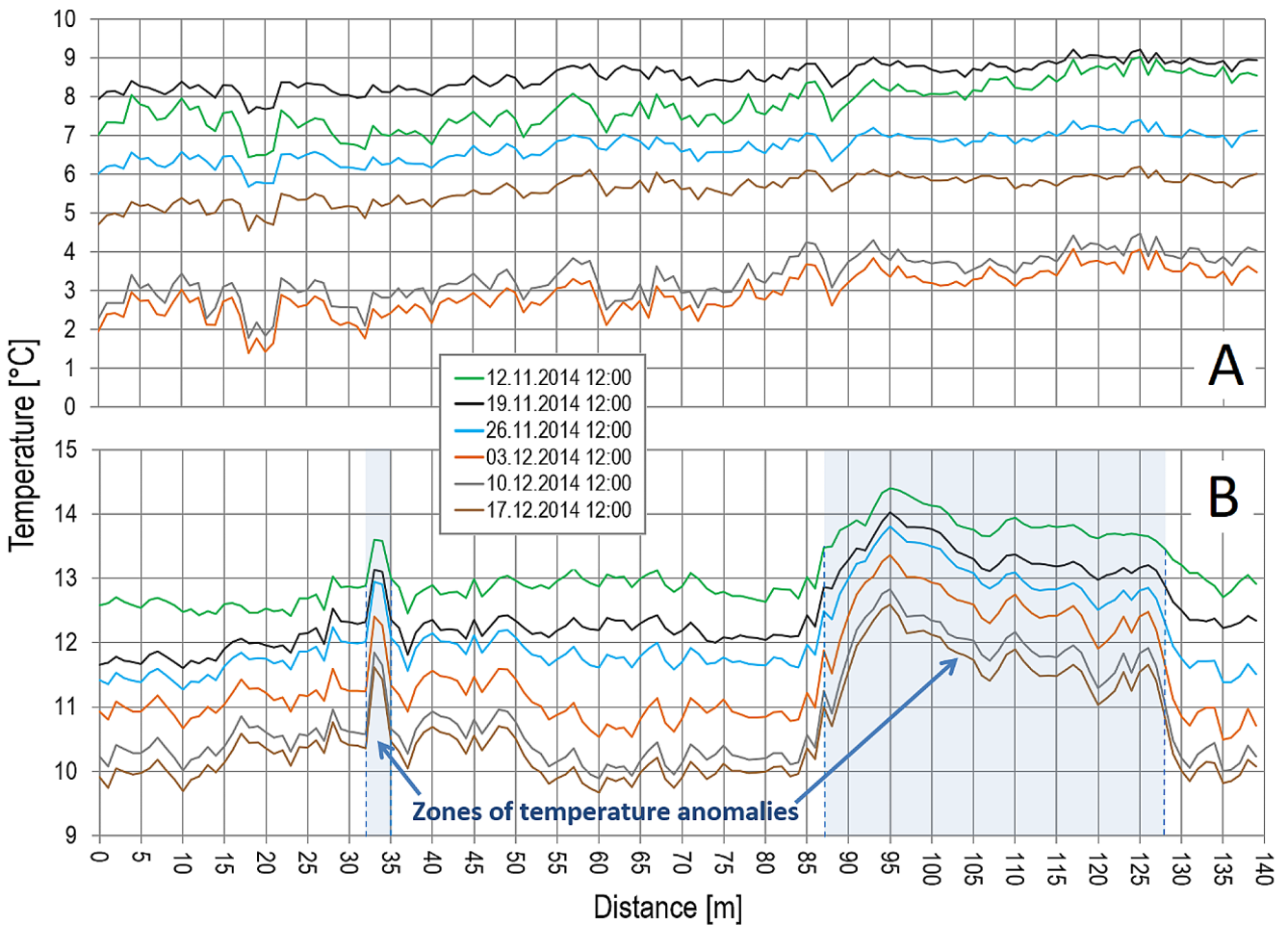


**Fig. 9** Thermal measurements conducted by two of the thermal-active sensors placed along the lower section of the Kozłowa Góra dam inside its downstream slope at a depth of 2.5 m

where:

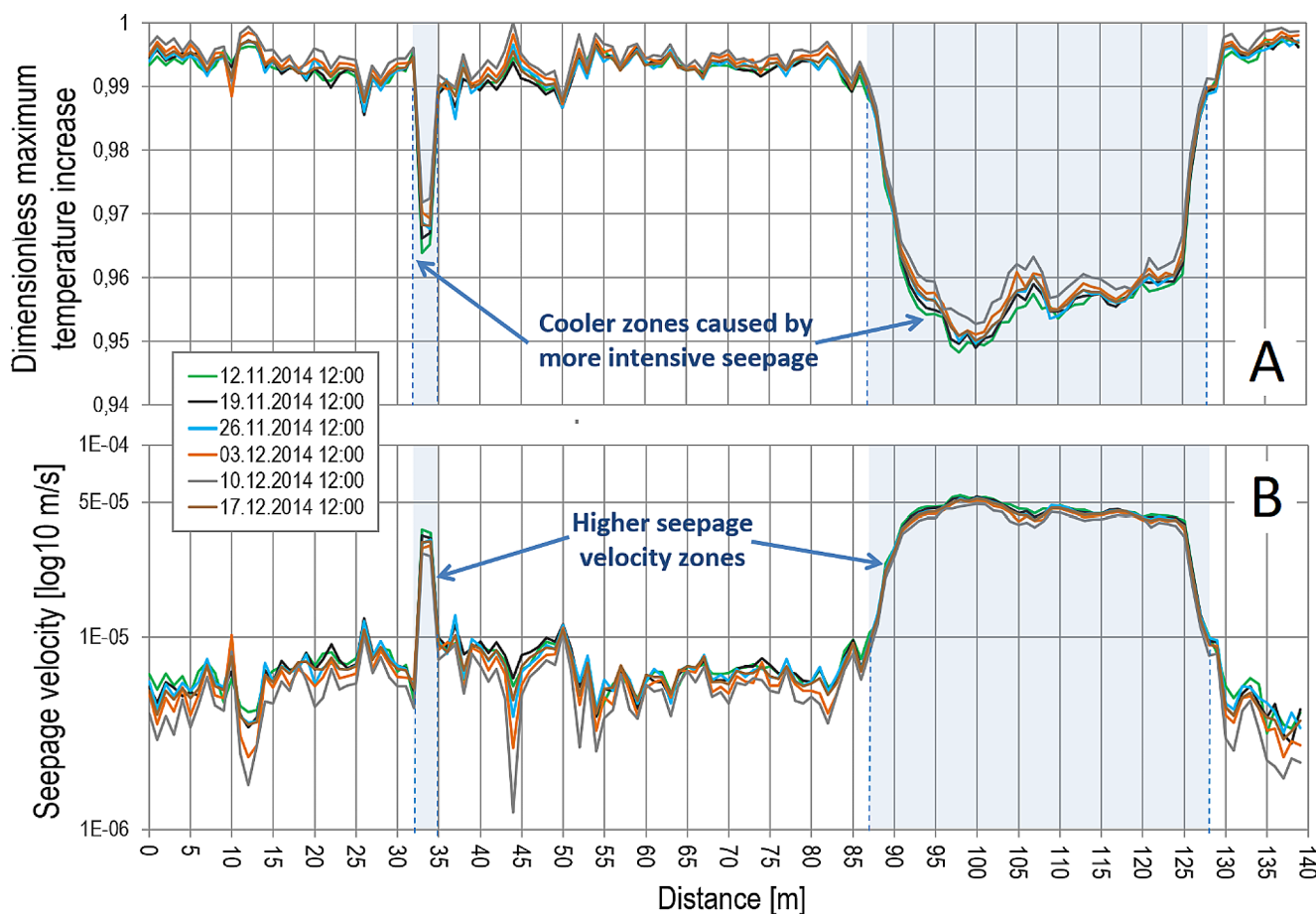
- $\Delta T_i$  = dimensionless temperature increment, (-)
- $T_i$  = sensor temperature at a given moment, (°C)
- $T_0$  = temperature of the first measurement at a given investigation (°C).
- $T_{max}$  = maximum temperature increment for a single sensor among all sensors along the monitored section of the dam during the five weeks of the study, (°C)

The compilation of passive measurements along the dam is depicted in Fig. 10, while thermal-active ones in Fig. 11. To enhance the clarity of result presentation in these figures, measurement values taken at the same midnight hour every 7 days are provided. In the later part of this chapter, we first expound on observations arising from measurements of the natural soil temperature. This serves as a preamble to the presentation of results attained through the application of the active method. The variability of natural soil temperature measurements over time at a depth of 2.5 m (Fig. 10B), shows a disrupted correlation with the variability of



**Fig. 10** Soil natural temperature at a depth of 0,25 m (A) and 2,5 m (B) measured along the dam inside the downstream bench





**Fig. 11** Thermal measurements carried out using thermal-active sensors along the dam inside the downstream bench at a depth of 2.5 m (A) and corresponding seepage velocities (B)

near-surface ground temperature (Fig. 10A). This is especially evident in the absence of a significant temperature increase in the zones from 32 m to 35 m and from 87 to 128 m at a depth of 2.5 m in relation to the temperatures measured in the near-surface zone of the ground. Another characteristic aspect is the systematic decrease in temperature during successive measurements at a depth of 2.5 m and the disruption of this regular temperature decrease pattern for near-surface measurements. For instance, the temperatures on November 12th are lower than those on November 19th in the near-surface measurements, while the opposite is true at a depth of 2.5 m. A significant rise in temperature ranging from 32 m to 35 m and from 87 m to 128 m, at a depth of 2.5 m is likely attributed to the influx of heat from deeper regions of the dam towards its downstream toe. The heat penetrates the dam’s structure and its subsoil from the reservoir side, particularly during earlier, warmer periods of the year, and is subsequently transported with increased water flow. However, this temperature increase is not readily apparent in near-surface ground temperature measurements for two primary reasons: firstly, these zones

are somewhat distanced from the layer of water flow within the ground, and secondly, they are primarily influenced by cooler actual ambient temperatures. In the context of earth dams, particularly larger ones, the presence of temperature zones shaped by two or more seasonal cycles—both warm and cold—is observable. In this particular case, an expert analysis of natural temperatures variation in Fig. 10B could indicate the possibility of more intensive seepage in the zones from 32 m to 35 m and from 87 to 128 m. This conclusion would be plausible, as thermal disturbances are quite distinctly evident against the backdrop of other temperature values, primarily due to the presence of an intensified seepage zone within the analysed section of the dam, as observed during the inspection conducted during the flood of 2010. Nevertheless, the expert analysis of natural soil temperatures in the near-surface zone, where various local external factors (shading, vegetation, local depressions, etc.) can significantly influence the surface heat distribution, is a highly challenging and often impossible task. In any case, credible confirmation of the correlation between temperature measurement disturbances and the presence of

intensified seepage would still necessitate the application of advanced signal analysis models. Nonetheless, this would only yield results defining the location of the seepage zones and qualitative differences in their intensity (Aufleger et al. 2005; Artiere et al. 2007; Khan et al. 2014; Radzicki and Bonelli 2012b). Furthermore, when comparing the temperature difference values between the higher temperatures in the zones from 32 m to 35 m and from 87 to 128 m with the temperatures around these zones, this difference consistently decreases with successive weeks of measurements. This phenomenon is related to the seasonal temperature variability, which, can lead to a reduction in thermal contrast between the temperature of the leakage zone and that of the surrounding ground during certain periods of the year. It might significantly diminish the chances of detecting intensified leakage, prolong the required measurement period for leak detection, and in extreme cases, could entirely preclude the possibility of leak detection when relying solely on the method of natural ground temperature analysis. From the above description, it is evident, that the utilization of natural temperature measurements for the analysis of seepage processes entails significant uncertainties and challenges. This particularly applies to measurements conducted in the near-surface zone of the soil, up to several meters below the surface.

In contrast to the natural ground temperature analysis, as demonstrated below, thermal-active analysis enables the derivation of considerably more unequivocal information about the seepage process. It enables the application of two methods to detect areas of intensified filtration. The first one is qualitative method. In this case, we compare the intensity of sensors warming. Locations where sensors significantly heated less compared to the remaining sensors are areas of intensified seepage. The results of applying this method are presented in Fig. 11A. It displays the dimensionless maximum temperature increase values for each sensor. It denotes the ratio of the maximum temperature increment measured by each sensor due to its heating to the maximum temperature increment observed across all measurements obtained from all heated sensors during the entire investigation. Two zones, ranging from 32 m to 35 m and from 87 to 128 m, exhibit significantly lower dimensionless temperature values compared to other zones. This discrepancy indicates a more intensive cooling effect of faster seepage in these zones. In the second quantitative method, the temperature rise curves registered in each thermally active measurement for every sensor were juxtaposed with laboratory-calibrated curves corresponding to various seepage velocities. This enabled the determination of the seepage velocity occurring around each sensor during each investigation. The results of employing the quantitative method are presented in Fig. 11B. The first important observation derived from

this subsequent step of analysis is that the seepage process occurs along the entire length of the analysed dam's section at a depth of 2.5 m, where the sensors are positioned. The temporal variation in seepage velocity in the monitored section during the study period was very low. This corresponds to the low variability of the water level in the reservoir in that time. The second observation is that the highest recorded seepage velocity there is  $5,4 \cdot 10^{-5}$  m/s. It was recorded for the sensor located at 98 m of the monitored section. This velocity is significantly below the critical velocity value of  $2 \cdot 10^{-2}$  m/s, which characterizes the potential for erosion process development. This velocity threshold was fixed by Fry (2012) based on a meta-analysis of research results encompassing all internal erosions processes. Conclusively, it can be affirmed that despite the intensified seepage in two zones ranging from 32 m to 35 m and from 87 to 128 m, no erosional processes likely occurred in either of them during the period of thermal-active investigations. It implies that the erosion processes observed on the dam (described in Chap. 3), most likely occurred in the more distant past, primarily during extended periods when the reservoir had higher water levels.

The determination of the exact cause of seepage anomalies is conducted by an expert. It relies on previous observations and, if necessary, additional research findings. In the case of the Kozłowa Góra dam, confirmation of the detected intensified seepage zone was firstly evidenced by the observation of a previously described local landslide of the dam's landside toe during the flood of 2010. Secondly, there are seven cross-sections where piezometers are installed on the dam. One of such cross-sections is located within the detected zone of intensified filtration. Statistical analysis of water level variability in all piezometers on the dam revealed that only in the piezometers within this zone, there is a consistent lowering of their water levels over the years. Its course is characteristic of the slow-paced, long-term process of suffusive internal erosion. Conversely, in all other piezometers, the opposite phenomenon of gradual water level rise over the years was observed. The likely cause of its increases was probably drainage clogging processes, as confirmed by the dam supervisor's observations (Radzicki et al. 2018). Furthermore, numerical two-dimensional modelling was conducted for this piezometric cross-section located within the monitored intensified seepage zone. It revealed the precise localization of the leakage zone within the dam cross-section. It was a fissure between the lower edge of wooden sheet piling installed in the alluvium subsoil and the roof of the rock layer beneath the alluvium.

The research results presented above demonstrate that the thermal-active method employing the Multi-Point sensor effectively allows for the identification of intensified seepage locations along an earth-damming structure. However,



the most crucial aspect of this method lies in its capability to determine the seepage velocity, thereby enabling a quantitative analysis of seepage processes. Consequently, it proves to be an efficient tool for studying these processes in existing damming structures. Considering the relatively quick installation time of the necessary equipment for implementing this method, especially the sensors, typical scenarios for its application may involve situations where the user of an earth dam or dike of a channel obtains information about the occurrence or development of seepage anomalies using a less accurate method and seeks to determine their parameters, such as their exact location, extent, or intensity. Examples of such information on seepage anomalies may include, but are not limited to, observed water exudates on the slopes of structures, abnormal increases in drainage expenses, abnormal variation or height of piezometric levels, or geophysical survey results indicating the presence of zones of loosening or percolation (ICOLD 2012, 2017).

In the article, we presented the first application of the Multi Point Thermal-Active Monitoring method in 2014 in application to an earth dam. Subsequently, over the ensuing years, this method underwent affirmative validation in the monitoring of various types of earth-damming structures. One of the applications included the detection of levee leaks along the Vistula River in Poland (Radzicki and Stoliński 2019), as well as those along the sea dike of the North Sea in the Netherlands (Radzicki et al. 2021). The described method was subsequently applied to further structures, including some of the largest European earth dams. However, due to confidentiality reasons, the results from the research findings were not published.

## Conclusions

Linear, fiber optic thermal cable traditionally used to monitor leaks and erosive processes in earth-damming structures as dams or levees presented significant constraints on their application in existing structures. A particular concern is the risk of creating preferential pathways for seepage and erosion during cable installation.

A novel geophysical investigative technique of Multi Point Thermal-Active Monitoring was developed to facilitate and propagate the application of thermal method in seepage processes investigations within existing dams and levees. Its originality lies in the insertion of a series of thermal sensors at the same depth in a line to achieve quasi-continuous measurements along the structure. Small openings created during sensors installation are secured with bentonite and do not pose a threat to the structure. Additionally, each of these sensors is equipped with a microheater. It enabling the application of a thermo-active method for

in-situ measurement of seepage velocity in the soil. This solution enables the rapid and secure installation of leak linear monitoring system along structure, even at significant depths greater than would be possible with the use of fiber optic cable.

The inaugural application of this novel technology occurred at the Kozłowa Góra dam situated in Poland in 2014. It was also the first application of the thermal monitoring in Poland for studying seepage processes, including leak detection, in earth-damming structures. The thermal sensors were installed at a depth of 2.5 m along a 139-meter section of the Kozłowa Góra dam inside its landside bench.

Qualitative and quantitative methods of active-thermal analysis were employed. The first method, based solely on heating the sensors, allowed for the detection of two leakage zones. More importantly, employing a quantitative approach with calibrated heating curves enabled precise determination of seepage velocities along the entire monitored section, encompassing also velocities in the leakage zones.”

The conducted studies have confirmed the effectiveness of the described Multi Point Thermal-Active Monitoring method in the application for monitoring seepage processes along an existing earth damming structures and significantly expands the methodology for investigating these processes in these structures.

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**Data availability** The data that support the findings of this study are available from the corresponding author upon reasonable request.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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