THE IMPORTANT ISSUES OF LEVEES MONITORING WITH SPECIAL ATTENTION TO THERMAL-MONITORING METHOD APPLICATION

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Abstract. Minimisation of the probability of a rupture of a flood protection dike is of primary importance when it can lead to significant material and/or social losses. Erosion processes are one of the major factors which cause dike collapses. In respect of the detection and assessment of the development of these processes, the “classical” methods used to date have very substantial limitations. This problem is discussed, inter alia, in the Introduction to this article. This concerns, in particular, the problem of the monitoring of a dike during a high water event. The linear thermal monitoring method, which has been intensively developed, especially in recent years, including the application of fiber optics distributed temperature sensing, has introduced a new quality to this issue. Its key advantages include continuous monitoring all along the structure, early and high spatial accuracy detection of the seepage and erosion processes and the possibility of analysing and assessing their development. This method has been extensively used for many years to monitor earth dams, whereas it is only recently that it has been implemented to monitor flood control dikes, in relation to the need to develop methods for data analysis and interpretation taking into account the manner of operation of flood control dikes.

This article describes the basic features of thermal monitoring and important aspects of its implementation for flood control dikes monitoring. It proposes elements of a methodology which combines a joint application of the methods used to date and the thermal monitoring method.

Keywords: Flood protection dike, Dike safety, Internal erosion, Seepage, Thermal monitoring, Methodology of dike monitoring, Fiber optic distributed temperature sensing

1. Introduction

The Floods Directive of the European Parliament and of the Council attributes particular significance to flood risk and imposes on the Member States the obligation to minimize this risk and to maximize measures to mitigate possible flood-related damage and losses. It requires systematic efforts and changes in many fields of management and flood protection the implementation of which will still take tens of years. At the same time, the developing climate change is likely to generate successive extreme weather events. One of the basic types of engineering facilities designed to protect against floods are flood control dikes which are thousands of kilometers long in many countries. For example, in Poland the total length of flood control dikes is about 8,500 km.

Dike collapses cause huge material and social losses, both direct ones and those that affect directly and on a long-term basis the development of the economy and the country. It is first of all important to ensure dike safety and to minimize the likelihood of their collapse. For example, according to the statistical data presented by Kledyński et al. (2012), in the course of one riverine flooding in 2010 in Poland there were 131 dike collapses causing the flooding of the space between the dikes. The related losses were estimated to reach at least several billion PLN. About 550, 000 ha were flooded, including 470,000 of farmland. The area was inhabited by 280,000, of which 35,000 were evacuated. In addition, in recent years, in other European countries, the United States and, in particular, in Asia, there were numerous, much greater floods than the one mentioned above, along with the ensuing flood-related losses.

Two main factors causing dike collapses are the water overtopping the dike crest and erosion processes (piping, contact erosion, suffusion) leading to the destruction of the internal structure of the body of the dike or the underlying ground through the washing away particles of the ground and/or the loss of stability of the body. For example, in the course of the 2010 flood in Poland, about 30% of dike collapses was caused by seepage and erosion-related factors (Kledyński et al., 2012).

At the same time, practically in all the countries with an expanded network of flood control dikes, nonmodernized dikes represent the major or important part of dikes. A substantial number of them are not in a satisfactory condition, either, and these dikes may be significantly likely to develop an internal destruction process. As a result, the detection and assessment of the development rate of the seepage and erosion processes in the course of a high-water event and a correct assessment of the technical condition of the dike following the high-water event are very important.

A number of methods can be used to acquire information on the condition and parameters of the body and the underlying ground relating to the seepage and erosion processes. Their correct selection is of key importance as a function of the type, scope and accuracy of the values of the parameters of the information gained, as well as the possibility and costs of applying these methods to achieve the expected effects; where the effect is not only the minimization of the risk of a dike break, but first of all the minimization of the probable overall losses, particularly in the areas protected by the dike.

The thermal monitoring method is one of the methods developed in several recent years to detect and analyze the seepage and erosion processes. In this article, we will try to demonstrate that this method qualitatively changes the previous possibilities of monitoring and assessing the technical condition of a flood control dike. The purpose of the article is to present the basic features of this method including significant results of research on it and its implementations. At the same time, it presents the current background to the issues related to the monitoring and assessment of the condition of flood control dikes, as well as a comments for the methodology for the application of methods for monitoring and assessing the condition of dikes, including the thermal monitoring method for the detection and assessment of the seepage and erosion processes.

2. Important aspects of the previous practice of monitoring and in-situ investigations on the seepage and erosion processes in flood control dikes

The hazard posed by an internal erosion process may ensue, inter alia, from neglect in the operation of dikes or the methods for their construction which more often than not deviated from the standards now in place. A substantial danger is posed by animal burrows and dens, or dead tree roots, which – in case of high water – can suddenly trigger a destruction process. Moreover, the erosion process can develop unnoticed from one case of high water to another. After a critical value of the local resistance of the ground has been exceeded, a surge in the growth rate of a process leading to a dike rupture is highly likely.

A number of conclusions are presented below concerning the previous practice of dike monitoring in the course of a high water event and after the event has ceased in respect of the detection and assessment of the seepage and erosion processes.

In the course of a high water event, practically the only methods used to date for dike monitoring have been visual methods, particularly a local inspection and the sporadically and locally applied thermal infrared method. "Classical" instrumental monitoring methods applied on earth dams, such as, for example, piezometric measurements or pore pressure measurements, practically have not been used on flood control dikes.

The development of an internal erosion process, particularly at its initial stage or even at its substantially advanced stage, is often imperceptible, even when using the abovementioned methods, especially at night, and particularly when a dike is covered by uncut grass or other vegetation. An example of an unexpected breakdown caused by an internal destruction process was the collapse of a dike section in the course of the 2010 flood at a bend of the Vistula River at the City of Cracow in Poland, which occurred at night without any prior signs of danger despite the inspections which had been carried out on the structure.

If the seepage and erosion process was detected in the course of a high water event there were no tools enabling the assessment of its parameters, including the prediction of its kinetics and the determination of the real hazard level. In consequence, more often than not the key decisions determining the allocation of manpower and equipment to secure the dike had to be taken on the basis of general information without having real knowledge as to which of the endangered places posed in fact the greatest danger and as to whether these were the only endangered places.

Assessments of the technical condition of flood control dikes are carried out in case of a current need; for example, following the passage of high water or when visible damage to a structure has been found and when required by the provisions of law. For example, in Poland the Construction Law (Construction Law, 2010) imposes the obligation to carry out an assessment of the technical condition of a dike and an assessment of its suitability for utilization at least every five years. According to the guidelines (Borys and Mosiej, 2003), the assessment of the condition carried out every five years must include geotechnical and geodetic tests. Moreover, these guidelines impose the obligation to perform a review of a dike every year in spring (i.e. a spring review) and suggest that another review (an autumn review) should also be carried out – with both representing a local inspection.

In most cases, the geotechnical tests (boreholes, soundings) designed to assess the technical condition of a structure are usually carried out at substantial intervals, even of several hundred meters. Since the distribution and degree of hazard in the dike body and the underlying ground are random and can be highly variable, even over a short dike section, the implementation of point geotechnical tests is highly insufficient for a real assessment of the condition of the dike. Let us emphasize that the application of geotechnical tests was, certainly, justified, but should be preceded by a prior exact determination of the location of a measurement point using other methods enabling an indication of the location of a weakened area of the ground. In particular, it is important to determine these zones where the development of the erosion process was invisible from the outside or was not discerned in the course of a high water event and/or a local inspection. A number of examples, including the one indicated by Gołębiowski (2012b), show that an inappropriate location of a geotechnical test and the absence of an additional testing method may lead to incorrect and often too optimistic conclusions concerning the condition of the dike. In turn, a very dense geotechnical testing would be expensive and could also cause a significant weakening of the dike structure (Gołębiowski, 2012b).

A piping, which is most dangerous with its possible growth rate, and also other forms of ground erosion, particularly at their initial development stage, can occupy a relatively small area of the dike cross-section. As a result of this, even relatively small distances in the location of a geotechnical measurement profile can lead to significant differences in the values of the ground parameters investigated.

In consequence, dikes are most often tested also using non-intrusive geophysical methods enabling the non-invasive testing of the dike body and the underlying ground in a continuous manner all along its length.

According to FloodPRoBe (2013), "geophysical investigation is based on the interaction between a physical field (e.g. electromagnetic field or mechanical wave propagation field) and the subsurface materials. These interactions are sensitive to material properties (nature and state parameters such as bulk density or moisture content). Therefore, geophysical investigations have shown great potential to inform on subsoil features such as: structure (layering), nature (geology), condition and spatial variations of soil properties". The emergence of contrasts imaged in the values of physical fields of the geophysical method applied, between consolidated zones and a degraded or damaged ground structure, enables the detection of the latter under specific conditions and in a specific range (Gołębiowski, 2012b).

Analysis of the literature, where some of the many relevant references include FloodPRoBe (2013), Fauchard and Meriaux (2007), Gołębiowski (2012a), indicates that the main methods applied for geophysical non-intrusive dike testing include the Ground Penetrating Radar (GPR), Magnetic Profiling, Electrical Resistivity Tomography, Seismic methods, Micro-Gravimetry. An example of GPR method application to detection of weakened zone is presented at Fig 1.

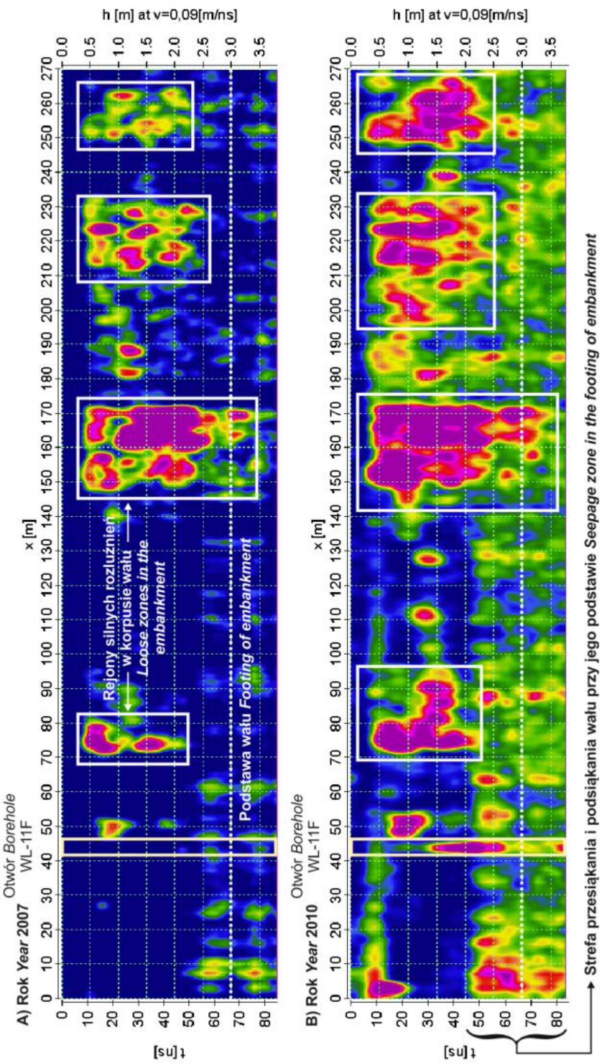

Fig 1. The results of GPR method application to detection of loose zones on the same section of a dike in: a) autumn 2007 after precipitation, b) May 2010, several days after a flood (Gołębiowski, 2012b)

Depending on the geophysical method used, in the course of a single day one measuring team can carry out an investigation of even a several kilometres long section of a dike (FloodPRoBe, 2013; Fauchard and Meriaux, 2007). Given that dikes can be tens and hundreds of kilometers long, this is a very important feature.

However, non-intrusive geophysical methods have a number of significant limitations. Citing FloodPRoBe (2013), "they only allow for indirect sub-surface investigation. Furthermore, some interpretation processes (e.g. data inversion) are complex and face 'equivalence' problems (non-unique solutions). The combination of data noise with inversion error inevitably leads to some model uncertainty". "Nevertheless, a potential risk of error remains. This fact has not always been well explained by geophysicists to geophysics end-users, which in turn has lead to some misunderstanding and disappointment". "Moreover, the most rapid geophysical investigation may not yield the highest resolution and reliability. Therefore, this issue is also a matter of risk/cost compromise".

It is hardly probable that relatively small, local changes, particularly those related to the initial development stage of erosion processes, can be identified using the abovementioned geophysical methods.

Despite their intensive development, the abovementioned geophysical methods are not likely to ever reach the spatial resolution and accuracy of measurements of the values of measured parameters which would correspond to instrumental intrusive methods.

In consequence, inter alia, FloodPRoBe (2013), Gołębiowski (2012a) and after Makowski and Popielski (2013), it is important to point out that the application of geophysical methods requires the use for a given section of several complementary geophysical methods or a calibration of the geophysical method using intrusive investigation techniques. More often than not, it is possible to find geophysical tests of flood control dikes where the conditions are not satisfied or the interpretation method itself is used insufficiently well and the interpretation results are sometimes highly doubtful.

To date, a number of research and development programmes have been carried out in the range of non-intrusive geophysical methods for testing flood control dikes. A number of studies have been performed, including those mentioned above, which contain guidelines and proposals for the methodology for the application of geophysical methods for dike testing. Their comparison shows some differences in emphasis on the suitability of individual methods. A continuous and intensive development of geophysical methods, in the scope of their equipment is underway, but primarily in the scope of methods for the analysis and interpretation of measurements. The competences of geophysicists' teams, conversion and interpretation algorithms and experience directly affect the results of analyses and the conclusions drawn on their basis.

3. Thermal monitoring method of the seepage and erosion processes

3.1 A new quality needed in the monitoring of hydraulic structures

On the basis of comments presented in Section 2 concerning the previous practice of monitoring and in-situ investigations on the seepage and erosion processes in flood control dikes, a thesis can be formulated that, particularly in the case of flood control dikes protecting the areas the flooding of which would cause significant losses or dike sections with already observed intensive seepage and erosion processes, it is necessary to use a monitoring system of the SHM type (structural health monitoring). This system should be characterized, in particular, by the following features (Radzicki, 2005; 2013):

• real-time monitoring of destruction processes during a high water event,
• continuous spatial monitoring of destruction processes all along the structure,
• early and high spatial accuracy detection of a destruction process,
• the possibility of assessing the kinetics of a destruction process,
• the possibility of developing an automatic alarm system to warn about the emergence of a destruction process,
• a damage- resistant unmanned system.

These conditions are met by a system based on linear temperature measurements and the method for thermal monitoring of the seepage and erosion processes.

For many years systems of this type have been applied in numerous cases to monitor earth dams (Aufleger et al. 2000; Johansson et al. 2000; Beck et al., 2010; Radzicki, 2009). The first system of this type has now been installed also on a dam in Poland (Radzicki, 2014).

In turn, in the case of flood control dikes, these systems have not been applied in many cases to date; they have so far been installed mainly in Germany and France (for example Courivaud, 2012). In Poland, it is also planned to install pilot sections of this system over the next year. It is only the recent years that saw an intensive development of this method for its application to monitor flood control dikes; this was related to the need to develop methods for data analysis and interpretation taking into account the character of the operation of flood control dikes.

A further part of this article presents the basics of the use of this method, its major features, methods for temperature measurements used in hydraulic engineering and important comments concerning methods for measurement analysis.

3.2 Coupled heat and water transport - the tool for detection and assessment of seepage and internal 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, piping, contact erosion) have characteristic features of their time and space development, demonstrated through the seepage field, also in the temperature field (Radzicki and Bonelli, 2010 and 2012, Beguin, 2011).

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

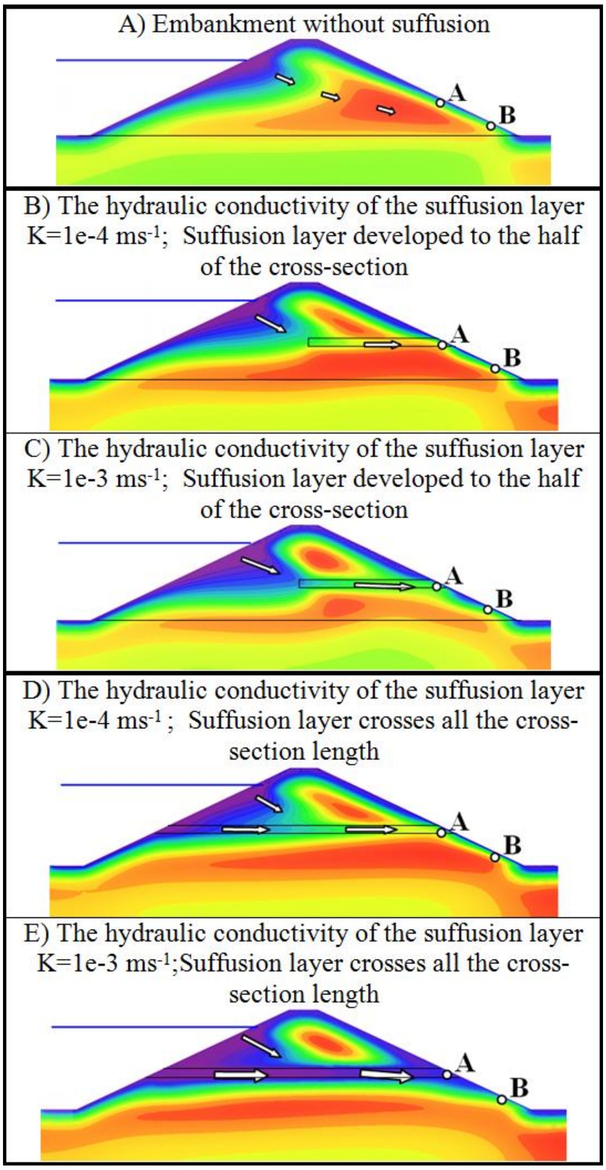

Fig 2. Temperature fields of a embankment cross-section registered at the same time instant for different lengths of suffusion layer and for different values of suffusion layer hydraulic conductivity (Radzicki and Bonelli, 2012)

As an example, Fig. 2 shows a numerical analysis of the impact of the different suffusion process development stages on the thermal field of a damming structure cross-section at the same time instant 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.

3.3 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.

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 meter and enables temperature measurements with a resolution of at least 0.1oC over a section of one cable up to 20 km long. The fiber optics applied to measure temperatures on hydraulic structures have watertight, armored jackets. This ensures their easy installation on the construction sites, tightness, very high strength and durability of at least several dozen years (Guidoux, 2008).

A technology alterative 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 meters 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 Neostrain presented at Fig. 3.

It has to be emphasized 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.

Fig 3. MCableS © multipoints temperature measurements cable (fot. Neostrain).

3.4 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 landside or downstream side of 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 analyzed.

For the existing dikes, installation of a linear temperature sensor in the structure downstream toe (Fig. 4A) 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 manifestation can be observed, 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 2009).

In the case of renovation or installation of the impervious membrane of which is located on the upstream side of dike, (Fig. 4B) a linear temperature sensor can be easily mounted below it. Thermal monitoring of this zone in question provides for early identifying of even a minimum point leakage in the membrane, as little as only about 0.2 l/min (Cunat 2010).

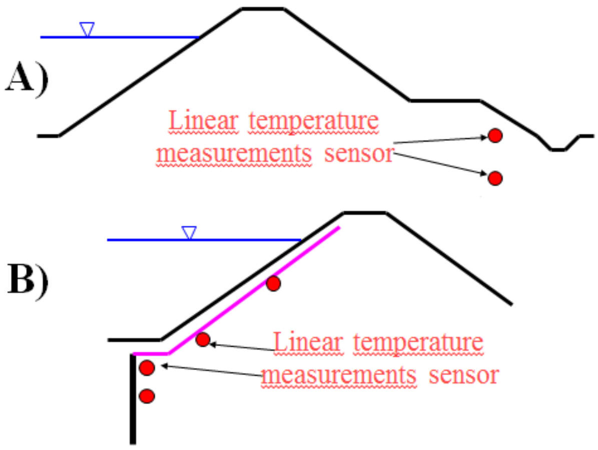

Fig 4. The example of locations of the temperature sensors in the existing levee for the thermal monitoring method application. A) in the downstream toe, B) below the upstream impervious membrane

3.5 Essential aspects of the application of the thermal monitoring method

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

In passive thermal monitoring, the natural temperature of a structure is analyzed. 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 relatively large part 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, Courivaud, 2012). The seepage rate is determined using exact solutions or the bases of temperature distribution functions elaborated on the basis of laboratory tests or numerical modelling, which are compared with the temperature values measured in reality at a measurement point. 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 heating for relatively long time 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 analyzed.

A key element which is necessary for carrying out effective, both passive and active, thermal monitoring of the seepage and erosion processes, in addition to the technology for linear temperature measurements, is the possession of tools and "know-how" enabling an analysis of temperature measurements and a readout of the information contained in them.

In the case of a passive thermal monitoring method, it is only since 2009 when the IjkDijk test was carried out that one can speak of a confirmed validation of this method in respect of the monitoring of flood control dikes. Given the important conclusions ensuing from this test, its objectives and major results are summarized below.

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 fiber optic temperature sensors made it possible for the first time to accurately visualize in time the course of the piping process in the real scale of the damming hydraulic structure (Fig. 5).

The analysis of temperature measurements by the Daily Analysis Model developed by EDF (France), which had been carried out for data measured by a fiber optic cable installed in the landside toe of the structure, proved to be particularly valuable (Beck et al., 2010). The Daily Analysis Model, which could operate in an automatic mode, localized points of the zones where the erosion process developed, even several days prior to the collapse of the structure.

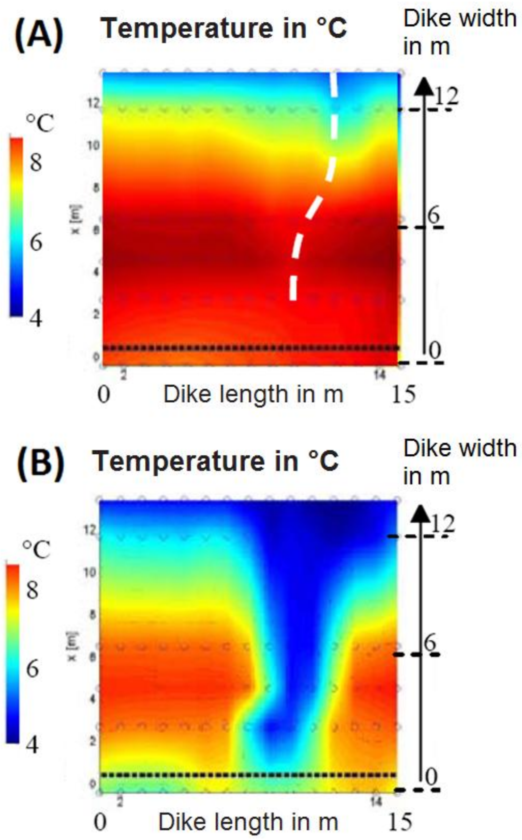

Fig 5. Temperature profiles (geophyConsult data processing), mapping from fiber optic GeoDetect® system in the foundation of the dike A) 22 hours before collapse B) 5 hours before collapse; elaborated after Artieres (2010)

4. Comments on the methodology for the monitoring and assessment of the seepage and erosion processes in flood control dikes, taking into account the thermal monitoring method

In summing up the information presented in Sections 2 and 3, it is possible to list the following groups of methods for acquiring in-situ information concerning the development of the seepage and erosion processes in flood control dikes:

1) Visual inspection
2) Non-intrusive geophysical methods
3) Intrusive geotechnical methods
4)Intrusive instrumental monitoring methods (including linear thermal monitoring methods)

Considering the advantages and limitations of the individual methods, they constitute a set of tools which can be adapted on a case by case basis for a specific structure. The variables of the function of this choice include, inter alia, the expected value of the minimization of the probability of a dike break, the risk of potential material and social losses, the results of the previous testing of the dike, the application costs of a method, the available resources, as well as the guidelines and requirements of the law in effect in a given country. The possibility of automatic detection of the seepage and erosion processes and the measurement of their parameters in the course of a high water event are also very important variables.

The elements of the methodology for the application of the methods listed above on flood control dikes are described in general below and a graphic schematic representation designed to illustrate with simplification the issue in question is shown in Fig. 6.

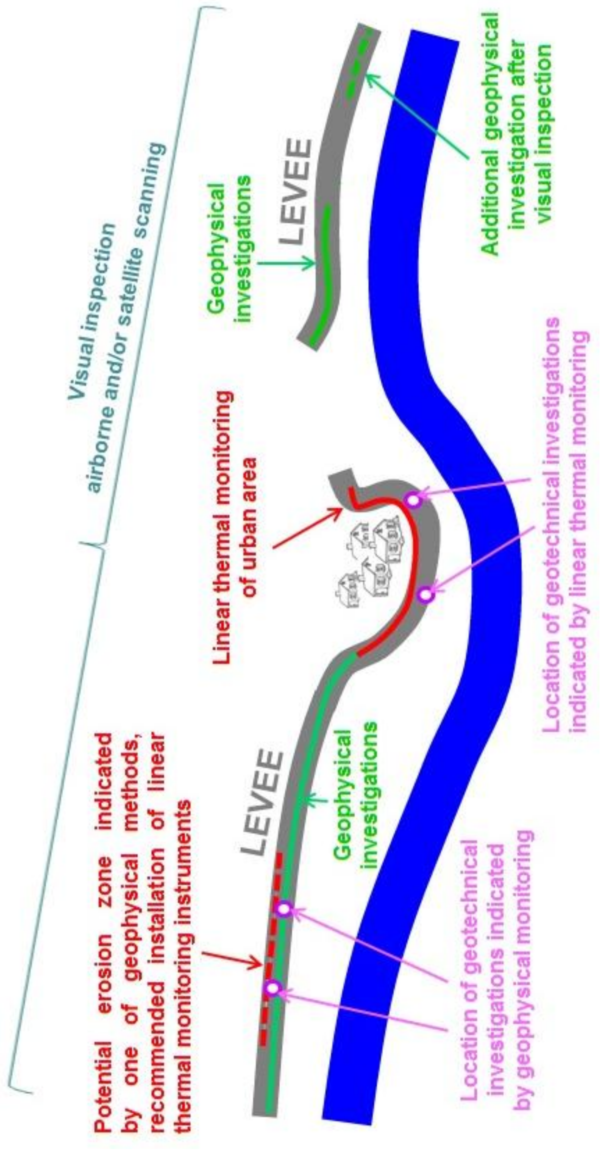

Fig 6. A graphic representation of elements of the methodology for in-situ dike testing discussed in the article.

In the course of a high water event and after the event, a visual inspection is the basic method for monitoring flood control dikes. Its essential tasks include, inter alia, the observation of signs indicating that an erosion process is underway in the dike.

Another group of methods applicable only in the course of a high water event consists of intrusive instrumental monitoring methods, one of the primary features of which is the possibility of unmanned instrumental dike monitoring. The linear thermal monitoring method is of particular importance in this group. It enables automatic detection of leakage and, in cooperation with trained experts, it allows for an analysis and assessment of the advancement of the seepage and erosion processes.

The information acquired by this method concerning the emergence of a destruction process, particularly at the initial stage of its development, as well as the data enabling the determination of the parameters of its time and space variability all along the dike monitored would represent some of the key information for the management of flood response activities in the course of a high water event.

The linear thermal monitoring method should primarily be used, firstly, at the dike sections protecting areas the flooding of which would cause substantial material and social losses, for example, very strongly urbanized, industrial areas etc. Secondly, it could be applied at the dike sections where zones of weakened ground or directly zones of intensified seepage and erosion processes have already been identified by other methods and those dike sections, for example, for which decisions are to be taken on their repair or repair outlays, which more often than takes in practice even several years. During this time thermal monitoring would enable the monitoring of destruction processes, while the information on their parameters and status would be important for optimizing the order of repairs and would also allow for their extent to be more aptly determined.

Whereas a linear continuous system for the thermal monitoring of the seepage and erosion processes all along the dike has been installed on an existing dike only at its landside toe, in the case of the detection of cross-sections with intensified seepage and erosion processes it can be supplemented at these cross-sections with additional measurement points. This will enable spatial monitoring of these processes (along and across the dike). These additional points can provide multi-parameter measurements (temperature, pressure, displacement) expanding the extent of essential information describing the parameters of the destructive process.

After a high water event, the results of measurements by intrusive instrumental monitoring methods would be valuable material describing the parameters of the seepage and erosion process all along the dike section monitored by these methods, enabling to a significant degree the implementation of an accurate and valuable assessment of its technical condition.

Another group of methods applied to acquire in-situ information concerning the development of the seepage and erosion processes consists of non-intrusive geophysical methods. The issues related to their application were already discussed in Section 2 Given their relatively simple and relatively inexpensive application method, the use of geophysical methods will be particularly important where thermal monitoring systems have not been installed – i.e. at present in the majority of flood control dikes. In turn, the application of a thermal monitoring method at one dike section in the course of a high water event and the application of non-intrusive geophysical methods after the high water event will make it possible to acquire the fullest spatial data possible concerning the variability of destruction processes in the dike body and the underlying ground.

On the basis of an analysis of data from the investigations performed using geophysical methods and linear measurements intrusive instrumental methods, particularly for the zones where destruction processes develop which have been identified by these methods, it is possible to precisely designate the points where geotechnical investigations should be carried out.

4. Conclusions

The article discusses important issues and the present status of research on a thermal method for monitoring the seepage and erosion processes. This method makes it possible to achieve a qualitative change in the monitoring of earth damming structure compared with the methods used to date. Its effectiveness was confirmed, inter alia, by independent research IJKDIJK tests carried out at real-scale test facilities.

The application of a linear thermal monitoring method, for example, fiber optic distributed temperature sensing, makes it possible to significantly enhance dike safety in the course of a high water event due to an early identification of the seepage and erosion processes and an assessment of the degree of their development.

Using this information, in the course of flood response activities it will be possible to optimize the utilization of manpower and material resources in order to protect the most endangered dike sections. After the end of high water event, detailed information on the identified seepage and erosion processes and their parameters enables the identification of cross-sections which require immediate repair and makes it possible to precisely define its extent. In consequence, apart from ensuring the safety of a structure, an important advantage of the application of the thermal monitoring method is the minimization of the repair costs and the optimization of the management of systems of hydraulic structures. For this reason, such installations emerge in increasingly large numbers all over the world.

Given the need to carry out installation works and their costs in the assembly of a thermal monitoring system, the localization of these systems on existing dikes is likely to be initially limited to sections which are of particularly large importance for flood safety. In contrast, it seems that there are no obstacles to the numerous application of the linear thermal monitoring method on newly built dikes, except for the need to gain the support of relevant decision-makers for this method. The pilot installations in a given country play a key role in this scope.

However, the thermal monitoring method is not envisioned to replace the previous methods for in-situ investigations on the seepage and erosion processes, i.e. especially local inspections, geophysical methods and geotechnical methods. All these methods constitute a set of tools which can be selected on a case by case basis for each dike section analyzed and the elements of its methodology have been presented in the article.

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