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THE CONCEPT OF QUASI-3D MONITORING OF SEEPAGE AND EROSION PROCESSES AND DEFORMATIONS IN DAMS AND DIKES, CONSIDERING IN PARTICULAR LINEAR MEASUREMENT SENSORS

KONCEPCJA MONITORINGU QUASI-3D PROCESÓW FILTRACYJNO-EROZYJNYCH W ZAPORACH I WAŁACH, ZE SZCZEGÓLNYM UWZGLĘDNIENIEM CZUJNIKÓW LINIOWYCH

A b s t r a c t

The primary purpose of this article is to present the concept of quasi-spatial monitoring of seepage and erosion processes and phenomena in the area of georisk, using invasive instrumental measurement methods, including, in particular, linear or quasi-linear measurement sensors. Along with the risk of water overflow over the crest of earth damming hydraulic structures, these processes and phenomena pose the main threats for their safety and are the main causes of their repairs. The proposed solutions seem to be valuable ones and have a high application potential. Taking into account the development of measurement methods and the field of the automatic control of the condition of a structure, they will probably be used increasingly frequently in the damming hydro-engineering constructions.

Keywords: dam and dike monitoring, condition assessment, automatic monitoring system, linear sensor, thermal monitoring, seepage, erosion, deformation

S t r e s z c z e n i e

W artykule skupiono się na przedstawieniu koncepcji quasi-przestrzennego monitoringu procesów filtracyjno-erozyjnych oraz zjawisk z obszaru georyzyka z zastosowaniem instrumentalnych, inwazyjnych metod pomiarowych ze szczególnym uwzględnieniem liniowych lub quasi-liniowych czujników pomiarowych. Te procesy i zjawiska, wraz z zagrożeniem przelania się wody przez koronę ziemnych obiektów piętrzących stanowią główne zagrożenia dla ich bezpieczeństwa oraz stanowią podstawowe przyczyny ich remontów. Zaproponowane rozwiązania wydają się cenne i mają duży potencjał aplikacyjny. Biorąc po uwagę rozwój metod pomiarowych oraz dziedziny automatycznej kontroli stanu konstrukcji prawdopodobnie będą stosowane coraz częściej w budownictwie hydrotechnicznym.

Słowa kluczowe: monitoring zapór i wałów, ocena stanu, automatyczny system kontroli technicznej, czujnik liniowy, termomonitoring, filtracja, erozja, przemieszczenie

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1. Introduction

Surveillance and monitoring systems of earth damming hydraulic structures play an important role in the monitoring and assessment of the condition of these structures.

A properly designed network of measurement sensors and, in particular, a system for automatic monitoring of the condition of an earth damming hydraulic structure and a correct analysis of the measurements carried out using them minimise the risk of their failure/collapse, especially when the early detection of destructive and unfavourable processes ensures that appropriately early preventive measures can be taken. The minimisation of the risk of a failure of a damming hydraulic structure limits the risk of potentially very serious flood related losses caused by the impact of a flood wave arising as a result of a breach of this structure. Moreover, an effective measurement system enabling the early detection and assessment of the growth rate and range of the destructive process makes it possible to minimise the costs of possible repairs. The accurate identification of the condition of a structure and its prediction for the future enable the optimisation of the repair policy. This is particularly important for the entities which manage the systems of damming hydraulic structures and operating and repair policy.

Particularly in the last decade, the abovementioned arguments and needs brought about the development of new innovative instrumental measurement methods, the implementation of measurement methods developed in other fields in hydro-engineering construction and the intensive development of the already existing methods. Given their application prospects and effects, particularly interesting devices include linear or quasi-linear sensors enabling, respectively, the linear or quasi-linear measurements of specific values along the section measured. The abovementioned trend in the development of measurement methods is, more broadly, part of the field of SHM (Structural Health Monitoring) which is developing intensively in the construction sector.

At present, measurement sensors are applied in particular for monitoring water dams, but, increasingly, they are also used to monitor flood protection dikes.

The primary purpose of this article is to present the concept of quasi-spatial monitoring of seepage and erosion processes and phenomena in the area of georisk, using invasive instrumental measurement methods, including, in particular, linear or quasi-linear measurement sensors. Along with the risk of water overflow over the crest of earth damming hydraulic structures, these processes and phenomena pose the main threats for their safety and are the main causes of their repairs.

2. The concept of the quasi-3D monitoring of risks in the area of georisk and seepage and erosion processes using instrumental methods

A potential ideal measurement method in the field of the monitoring of the condition of a structure should enable in particular: the early detection of a threat at any place in the structure and the exact identification of its location and range, as well as enable the determination of the growth date of a possible destructive process. In consequence, it should be characterised, inter alia, by a high resolution of measurements, along with a simultaneous measurement of the values of the measured parameters in a continuous manner in space and the possibility of implementing this method in automatic systems of measurements for their periodical or incidental condition assessment or/and real time monitoring of the conditions of a structure on a 24/7 basis. Other expected features would also include low cost and easy application. Certainly, these features would also be desirable for the methods applied in hydro-engineering construction [7, 9].

At the present level of the development of measurement methods, there is no such ideal method which would demonstrate, at the same time, all the features listed above. In consequence, it is necessary to use a set of measurement solutions, in accordance with a suitable methodology which, depending on the needs, makes it possible to achieve to the optimum extent the most important expected results. Each time, these solutions are adapted to the individual case of a structure. It should be noted that the abovementioned methodology also develops along with the advancement of measurement methods and the growth of knowledge in a given area.

In the monitoring of hydraulic structures, particularly given the frequently large dimensions of these structures, in terms of both their cross-section and especially their length, a very important feature of the monitoring method is the possibility of making spatial measurements, in particular in a continuous manner along the length of the structure. Such a possibility is offered by non-invasive geophysical methods, including the method of electrical resistivity or seismic tomography. These methods are important tools for examining damming hydraulic structures; however, they have a number of limitations [4, 3, 9]. It can be expected that, despite their intensive development, non-invasive geophysical methods are not likely to achieve the spatial resolution and accuracy of invasive measurements by instrumental methods. It is hardly likely that relatively small, local changes in the ground medium, particularly those related to the initial phase of the development of destructive processes, can be identified using non-invasive geophysical methods. In turn, early information on such changes – the growth rate of which in the case of damming hydraulic structures under the pressure of dammed-up water can be very high – is important for the assessment of their condition and the prevention of possible threats [4, 9]. On the other hand, invasive instrumental methods do not enable a full extent of spatial measurements. When, in turn, invasive instrumental methods are considered, they do not enable the full implementation of spatial measurements. However, the use, firstly, of the appropriate measurement tools and, secondly, of the appropriate methodology for their application make it together possible to achieve the effect of quasi-spatial (quasi-3D) measurements.

At present, it is interesting to note two groups of instrumental methods which make it possible to achieve the effect of quasi-3D measurements and offer a significant application potential in the range of hydro-engineering construction. The first one is the thermal method for the detection of seepage and erosion processes, while the other is a set of measurement tools enabling the monitoring of deformations of the medium investigated. In both, the key element is a linear measurement sensor enabling continuous or quasi-continuous linear measurements in space. Depending on the needs, it is installed in the main body and/or the foundation along the length of the hydraulic structure. Such a solution enables the detection of places and cross-sections where an adverse phenomenon or process is occurring along the length of the structure.

Obviously, the more linear sensors are placed in the cross-section of the hydraulic structure, the fuller the effect of the quasi-spatial monitoring achieved. However, on the other hand, as the number of sensors grows the costs of the monitoring system increase and also the construction work becomes more complicated, in the case of a newly built or repaired hydraulic structure. Therefore, the essence of more effective systems for quasi-3D measurements is the design of the optimum number and locations of linear sensors which would make it possible to acquire information on the key zones of the hydraulic structure along its length.

The linear measurement along the length of the structure is supplemented with appropriately situated single sensors or also with the abovementioned linear sensors in selected cross-sections of the hydraulic structure in order to ensure fuller, quasi-spatial monitoring of the destructive process. Sensors in the measurement cross-sections of the hydraulic structure can be planned and installed beforehand at the places of the expected potential largest adverse changes and the highest risk, including georisk, e.g. the largest computational consolidation deformations. Where necessary, they can also be added to the necessary extent in a cross-section where an adverse phenomenon has occurred, after the cross-section at risk has been identified by the linear monitoring system installed along the length of the hydraulic structure. Both of the abovementioned methods are described in greater detail in the subsequent sections of the article.

3. The method for the thermal monitoring of seepage and erosion processes in the concept of quasi-3D monitoring

Internal erosion is one of the basic threats for dams and dikes. Appropriate monitoring of this process is of key importance for ensuring the safety of these structures and minimising the costs of their possible repairs. Among the existing methods for monitoring seepage and erosion processes, the thermal monitoring method has become particularly valuable and increasingly popular in recent years [5, 6].

Thermal methods for analysis of water flow in the ground are based on the relations between heat and fluid transport processes, which are coupled processes. A change in the moisture content of the ground, in particular, the emergence of water seepage and changes in its velocity, significantly disturb the heat distribution in the body of the structure and the underlying ground. Since the erosion process affects the seepage vector field, it also directly influences the temperature field of the ground medium.

Each of the erosion process types causes a characteristic disturbance in the hydro-thermal field [11, 12]. In consequence, the thermal monitoring method allows for the detection and analysis of both seepage and erosion processes.

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

The method for the thermal monitoring of seepage and erosion processes and examples of its applications have been described in many articles, including e.g. [2, 8, 10].

One of the reasons for the success of the thermal monitoring method is 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 in the structure.

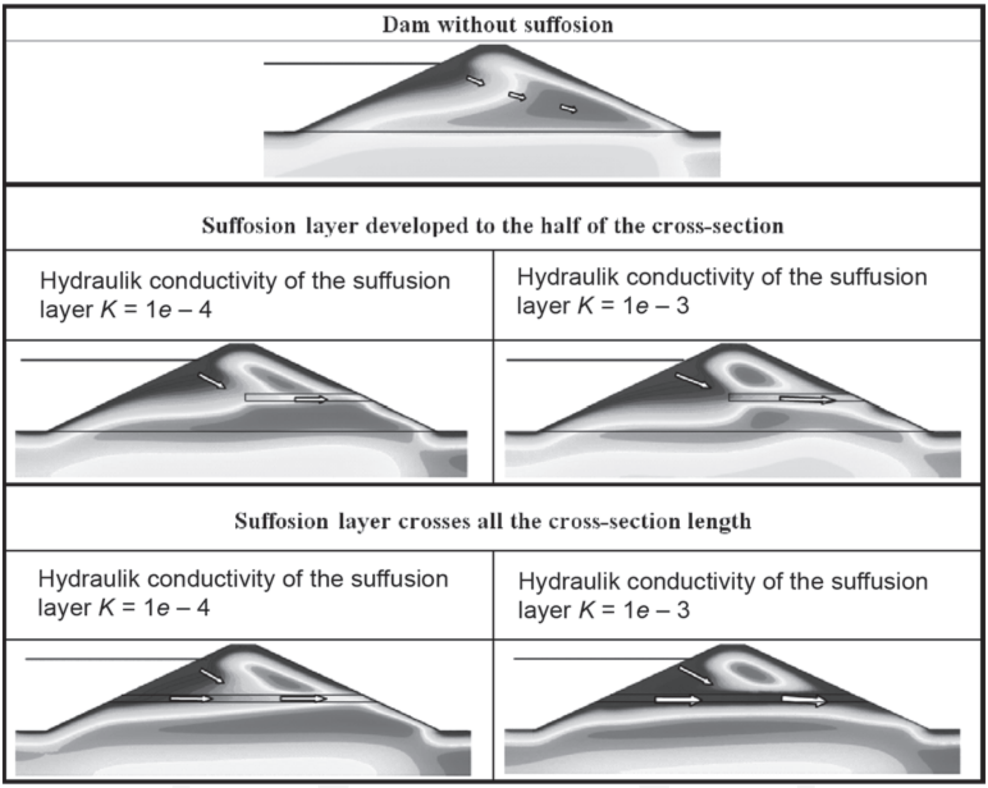

Fig. 1. Temperature fields of a dam cross-section registered at the same time instant for different lengths of the suffusion layer and for different values of suffusion layer hydraulic conductivity [12]

One of the linear technologies applied in thermal monitoring entails temperature measurements using a fibre optic using the spectral analysis of backscattering and its comparison with the spectrum of the light fed into the fibre by a laser [14]. 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 metre and enables temperature measurements with a resolution of at least 0.1°C over a section of one cable up to tens of kilometres in length. The fibre optics applied to measure temperatures on hydraulic structures have watertight, armoured jackets. This ensures their easy installation on the construction sites, tightness, very high strength and durability of at least several dozen years.

Technologies alterative to fibre optics are two solutions which will be called the "multi sensor cable" technology and "multi hammered points sensor" [13].

The "multi sensor cable" is 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 main advantage of this solution for short measurement sections of up to several hundred metres is its cost which is even several times lower than that of a fibre optic-based thermal monitoring system. An example of such a "multi sensor cable" is MCableS® from

Neostrain [13]. In addition to its installation along a structure, the "multi sensor cable" technology is also applied in water temperature measurements in piezometers. Given its small diameter, a "multi sensor cable" does not prevent manual periodic measurements in a piezometer, which are more often than not required for dams in order to verify automatic pressure measurements.

The "multi hammered points sensor" is mounted without excavation by inserting successive sensors in a series, one after another. 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. It is easy and cheap to "replace" a damaged sensor in the measurement system. Near a damaged sensor, a new sensor is inserted and incorporated into the system. Coupled with the no-excavation installation, application of multi hammered points sensor 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 situations where for different reasons it is impossible or difficult to carry out earthworks. An example of a "multi hammered points sensor" is MPointS® [13].

In both these measurement solutions 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 above-mentioned technologies 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.

The combination of continuous temperature measurements along a retaining hydraulic structure and vertical measurements of temperature profiles carried out in selected cross-sections of the structure enables a more detailed quasi 3D analysis of destruction processes in the cross-section of interest here. After a destruction process has been detected to develop along the hydraulic structure using the linear measurement method, additional vertical

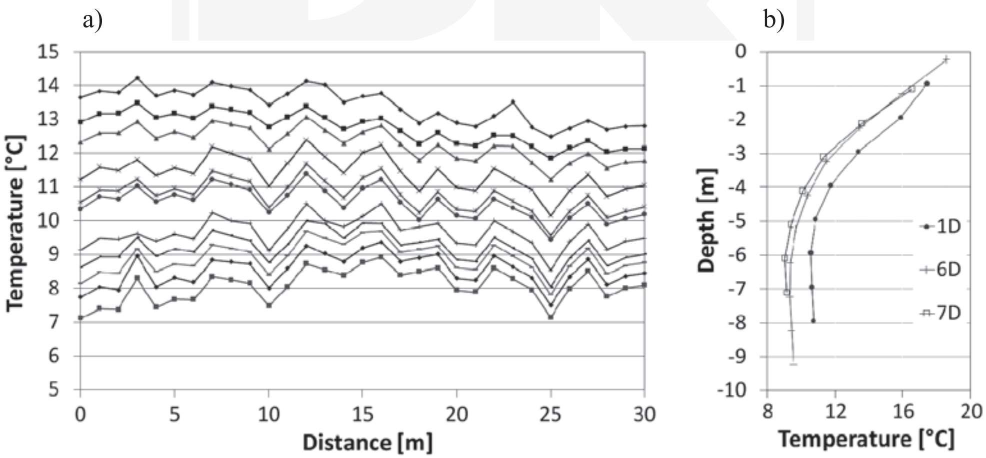

Fig. 2. An example of temperature measurements carried out on the Kozłowa Góra Dam:
a) in a section of a linear sensor installed along the dam in its downstream toe, b) in a vertical measurement profile

temperature measurements can be carried out in this cross-section. Depending on the needs, the abovementioned method for water temperature measurements in a piezometer can be applied for this purpose; however, particularly in the case of hydraulic structures which periodically dam up water, such as e.g. flood control dikes, sensors which are driven or drilled directly into the ground can be used.

The system for quasi-3D thermal monitoring considered here was designed and installed on the Kozłowa Góra Dam, where MPointS® was run along the dam, while in its cross-sections, in piezometers, a MCableS® was installed to carry out the measurements of vertical temperature profiles. Fig. 2 shows an example of a temperature measurement implemented using this system.

4. Deformation measurements by the instrumental method in the concept of quasi-3D monitoring

Deformation measurements are an important element in the monitoring of destructive phenomena and processes unfolding in the foundation and/or the main body of a damming hydraulic structure. A significant risk of deformations of hydraulic structures can result, inter alia, from the large dimensions of a hydraulic structure, i.e. the substantial loads generated by water damming in a reservoir, and seepage processes. Moreover, in general, civil structures, including hydraulic structures, are increasingly often localised in areas of enhanced georisk. Such areas are those where adverse geological phenomena occur (e.g. karstic phenomena and formations, landslides, suffusion, floating earth, glacitectonic effects) and areas degraded by man (in particular, the areas where mines and steelworks used to operate).

In the case where investment projects are carried out on weak soils, an appropriately selected monitoring system will provide investors with information about possible non-uniform subsidence, soil push-out from under a structure, tilting and displacements of a structure, the degree of consolidation of the underlying ground etc. In effect, this valuable information provides the basis for the adoption of the optimum decisions in the course of an investment process, the correct management of work, and, after its completion, the monitoring and acquisition of accurate assessments of the condition of the hydraulic structure.

In accordance with the concept of the quasi-spatial deformation monitoring as proposed in Section 2, its basic element is a linear or quasi-linear displacement sensor. Such a sensor could be a fibre optic sensor, which operates in the same way as the previously described temperature sensor, i.e. on the basis of the analysis of the spectrum of light dispersed in the fibre optic [1]. However, at present, these sensors have a number of limitations: they only enable a qualitative measurement of deformations; have low tensile strength (sensors with a glass core) and have a relatively very expensive measuring head. Another interesting measurement solution enabling quasi-linear measurements of vertical displacements in a pre-determined measurement profile up to several hundred metres long, with an accuracy of up to single millimetres is a hydroprofile meter. In this device, the measurement sensor is a hose through which a liquid is pushed. The level of the liquid is measured at pre-determined points relative to the reference level, determining the position of the hose at these points. An adequately dense measurement of the position points of the measuring hose makes it possible to achieve quasi-continuous measurements.

Hydroprofile meters are ever more widely used for monitoring embankments and foundations in civil engineering, particularly for monitoring road embankments. However, they have not been often used for hydraulic structures.

In the quasi-3D deformation monitoring system, linear monitoring using a hydroprofile meter can be complemented with classical point deformation sensors, selected on a case by case basis for a given issue and enabling its broader assessment in terms of both the parameters measured and their spatial distribution. These sensors can include inclinometers, extensometers, hydro-levelling instruments and others.

5. An example of the quasi-3D system for the monitoring of seepage and erosion processes and deformations in an earth dam

Both of the measurement methods for the quasi-3D monitoring of the seepage and erosion processes and deformations described in the previous sections were proposed as elements of the monitoring of one of the earth dams which are now at the design stage in Eastern Europe. A schematic diagram of the proposed monitoring solution is shown in Fig. 4. This dam, of a planned height of a dozen or so metres, will have a waterproof element (represented by a yellow colour in Fig. 3) on the waterside, which will be linked to the cut-off wall planned in the ground underlying the waterside toe of the hydraulic structure.

The concept of the quasi-3D system for the monitoring of this dam is, firstly, based on linear systems for the thermal monitoring of seepage and erosion processes and displacements, continuous along the length of the dam. Another important element of this concept are vertical temperature and displacement measurement profiles placed in selected measurement cross-sections of the hydraulic structure. These cross-sections are situated along the entire length of the dam, in particular in the zones of the highest potential risk, including those of the highest georisk caused by the existence of weaker soils in the ground underlying the zones.

In the scope of the thermal monitoring system, the design includes the installation in the main body of the dam of linear fibre optic temperature sensors placed along the entire length of the dam in two zones. The first zone is the space of the main body situated directly close to the waterproof element of the dam, on its upstream side. The other zone is the downstream toe of the dam. Minimising the costs of the thermal monitoring system, such a localisation of linear fibre optic temperature sensors enables the linear monitoring of both the zone of potential penetration of the leak into the hydraulic structure and its very early detection, and also makes it possible to control the zone of the potential accumulation of the leak on the downstream side.

In addition, in planned measurement cross-sections, it was proposed that vertical thermometric profiles should be placed in piezometers. They complement the quasi-3D system for the monitoring of the dam with the possibility of its hydrothermal analysis also in its transverse planes with respect to the system of linear sensors.

The temperature measurements in the main body of the dam would also be complemented with a system of the measurements of external thermal loads acting on the dam, including appropriately designed systems for measuring the temperatures of the air and the water in the reservoir.

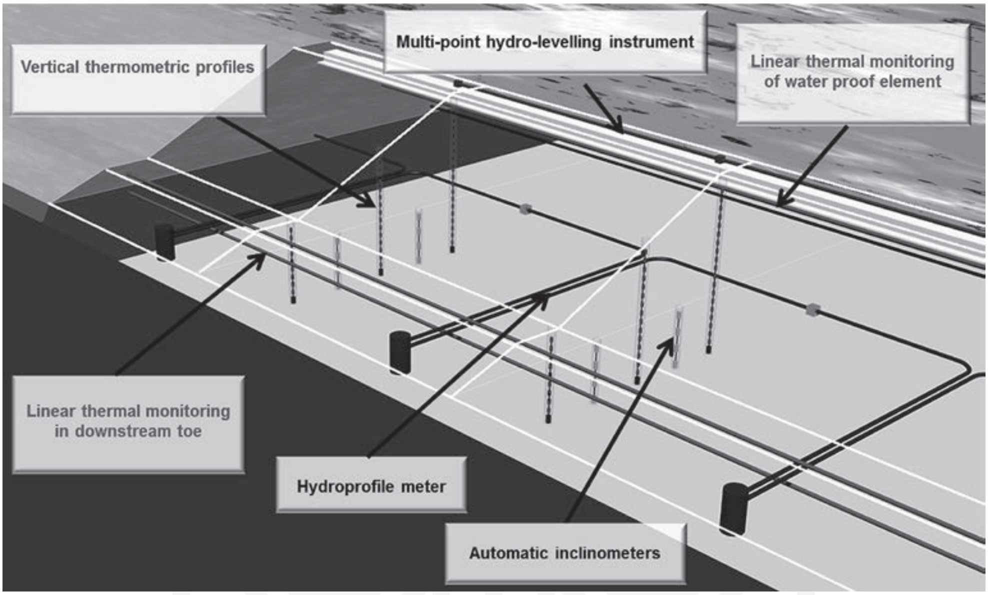

Fig. 3. Elements of the setup of quasi-spatial systems for the thermal monitoring of seepage and erosion processes and deformation monitoring

In the scope of the quasi-3D system for measuring deformations of the dam, hydroprofile meters were chosen for the linear monitoring of vertical displacements along the length of the dam. The measuring hoses of the hydroprofile meters are placed in the zone of contact between the main body of the dam and the underlying ground in order to directly measure the impact of displacements of the ground underlying the dam on its main body. The measurement section of each of the hydroprofile meter begins with a measurement and access well (blue cylinders in Fig. 3), situated in the downstream toe of the dam. From the well, the measuring hose enters the main body of the dam. The hose runs along the axis of the dam, turns and runs along the axis, finally to return to the successive well which is, at the same time, the initial well for another hydroprofile meter. This arrangement ensures the continuity of measurements along the axis of the dam and, in addition, continuous horizontal profiles of vertical displacements between the axis of the dam and the measurement and access wells.

The linear system for measurements of horizontal deformations along the dam is complemented by the vertical profiles of automatic inclinometers situated in the planned measurement cross-sections of the dam. Moreover, the sensors of automatic multi-point hydro-levelling instruments are placed on the crest of the dam, enabling high-precision measurements of the vertical displacements of this element of the dam.

The system for the monitoring of the dam is complemented with other sensors, including benchmarks, pressure sensors in piezometers, instruments for measuring drainage discharges etc.

6. Final remarks

The development of measurement methods and the development of the methodology for their measurements and analysis, including the development of automatic systems for controlling the condition of built structures, make it possible to use more efficient and effective measurement solutions. This also applies to hydro-engineering construction, in particular damming hydraulic structures, such as dams and flood protection dikes. For these structures, the minimisation of the risk of failure and/or repairs is a very important issue.

The linear sensors for the thermal monitoring of seepage and erosion processes and displacements presented in the article seem to have a very high potential for the application in the monitoring of damming structures for which the monitoring of these parameters is particularly important in the assessment of their safety and condition.

The article presents in particular the concept of quasi-spatial monitoring of seepage and erosion processes and displacements. This is a solution the application of which uses especially the advantages of linear sensors and is based on their appropriate use in the system for monitoring a hydraulic structure.

The proposed solutions seem to be valuable ones and have a high application potential. Taking into account the development of measurement methods and the field of the automatic control of the condition of a structure, they will probably be used increasingly frequently in hydro-engineering construction.

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