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PAWEŁ OPALIŃSKI, KRZYSZTOF RADZICKI*, STEPHANE BONELLI**

NUMERICAL MODELLING OF COUPLED HEAT AND WATER TRANSPORT ON EMBANKMENT DAM IN KOZLOWA GORA

MODELOWANIE SPRZĘŻONEGO TRANSPORTU CIEPŁA I WODY W ZAPORZE ZIEMNEJ W KOZŁOWEJ GÓRZE

A b s t r a c t

The paper discusses the use of the thermo-hydraulic numerical model to verify the hypothesis of subsoil seepage and erosion development in a section of the Kozłówa Góra dam. This dam is provided with an innovative and advanced system for quasi-3D thermal monitoring of seepage and erosion, which was used for temperature measurements. The herein reported analysis of the measurements showed high applicability of the thermal monitoring method in determining the severity of erosion and seepage processes using numerical modelling.

Keywords: earth dam, thermal monitoring, numerical modelling

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

W artykule przedstawiono wykorzystanie termo-hydraulicznego modelu numerycznego w celu weryfikacji hipotezy o rozwoju procesów filtracyjno-erozyjnych w podłożu w jednym z przekrojów zapory Kozłowa Góra. Zapora ta posiada innowacyjny, zaawansowany, system termomonitoringu quasi 3D procesów filtracyjno-erozyjnych, który został wykorzystany do realizacji pomiarów temperatury. Przedstawiona w niniejszym artykule analiza pomiarów wykazała dużą przydatność metody termomonitoringu w określaniu stopnia nasilenia procesów filtracyjno-erozyjnych z zastosowaniem modelowania numerycznego.

Słowa kluczowe: zapora ziemna, termomonitoring, modelowanie numeryczne

* M.Sc. Eng. Paweł Opaliński, Ph.D. Eng., Krzysztof Radzicki, Institute of Water Engineering and Management, Faculty of Environmental Engineering, Cracow University of Technology.

** Ph.D. Stephane Bonelli, Hydraulic Structures and Hydrology, National Research Institute of Science and Technology for Environment and Agriculture.

1. Introduction

Thermal monitoring methods are currently recommended and considered the most promising for the detection and evaluation of seepage and erosion phenomena in earth dams [3, 7, 8]. Changes in the thermal field caused by seepage and leakage through the dam body or foundation allow for the assessment of the intensity of these processes as well as an indirect analysis of the erosion processes.

The Kozłowa Góra earth dam on Świerklaniecki reservoir, an important flood protection and Upper Silesia regional water supply asset, has been provided with Poland's first modern and innovative thermal monitoring system [16], also designed as a field R&D laboratory for seepage/erosion thermal monitoring method development. The Kozłowa Góra earth dam is owned by Górnośląskiego Przedsiębiorstwa Wodociągowego S.A., a regional water company.

At the dam, several seepage/erosion phenomena have been observed. In the 2010 flood, a piece of downstream slope lost stability at the perimeter ditch. The observations, research and analyses, including those defined in the dam condition's evaluation, suggest two development mechanism of seepage and erosion in the dam body and foundation. The first is leaking in the upper part of the inclined clay core and development of a privileged seepage path towards the downstream toe in the dam's main static body. The other is erosion in the dam foundation related to the sheet piles' under-depth and/or leakage. These hypotheses are widely described in chapter 4.

Thermometric measurements at the Kozłowa Góra main dam have been taken since 2014. Due to the relatively low water level at that time, the first hypothesis could not be verified, and this article reports an analysis of the second hypothesis by the thermal monitoring method.

Thermal monitoring offers a wide array of temperature measurement analysis tools [8, 15]. They also include thermal-hydraulic numerical models of the test object. Such a model of transient heat and water transfer was developed for piezometric cross section No. 6 of the dam. This cross-section is located in the area of the 2010 ditch slope failure. To define the model's boundary conditions, a series of upstream and downstream slope temperature measurements was used, taken at different heights on both slopes of the dam, and upper and lower water levels. The period from the 24th of May to the 4th August 2015 was modelled.

2. The Kozłowa Góra Dam

The Kozłowa Góra main dam was made of locally available material. It is a class II, 6 m high dam, built in 1933 and 1939 as a temporary facility for military purposes, i.e. flooding the downstream areas. In line with the reservoir's intended purpose, the technical requirements for permanent damming hydro-engineering structures were ignored in the dam's construction. Material for the embankments was not properly sorted, and the embankment density was neither proper nor controlled in the earthworks [5, 9, 17]. The dam body is made of sandstone and limestone fragments, sand and silt sand. The waterproof element is the inclined pre-quaternary clay core, 0.70 m thick at base and 0.18 m at the top (altitude 279.19 m OSL). Seepage in the foundation under the dam is limited by a wooden sheet pile set at the toe of the upstream slope. It connects to the inclined clay core, forming a 600 m long waterproof element. The clay core is protected by 1.60 m thick gravel layer. The upstream slope is protected by 30–35 cm thick stone block paving laid on cement mortar (Fig. 1).

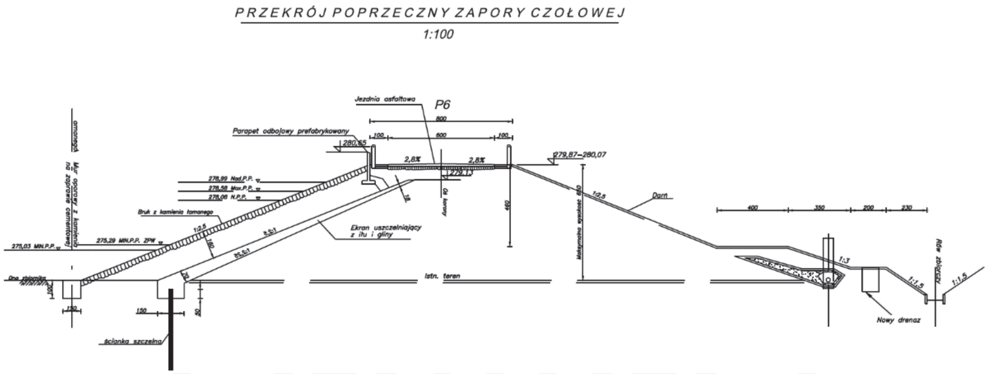


Fig. 1. Typical cross-section of the Kozłowa Góra frontal dam body

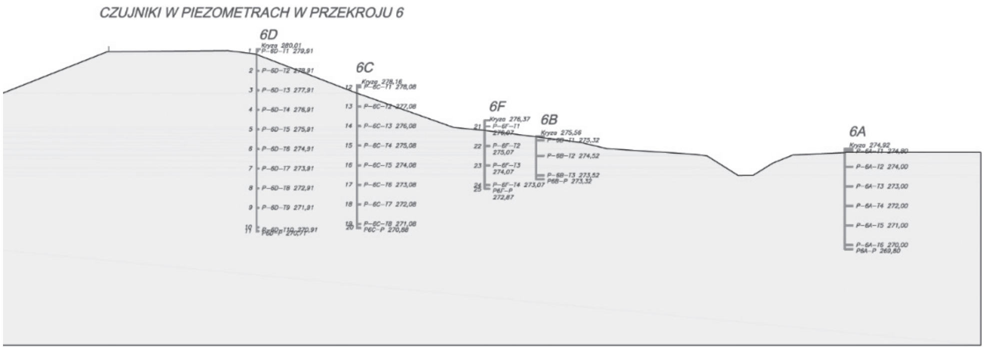


Fig. 2. Fragment of the Kozłowa Góra dam's downstream side cross-section with thermal sensors installed in piezometers

The downstream slope is planted with grass and divided by two 4.0 m × 2.0 m benches. Frontal dam seepage water is drained through ceramic drains in aggregate surround of three-layer gravel filter set in the downstream slope toe. Water from the drains flows to an open ditch running at 6 m distance from the drainage axis. On the upstream side, the crest is protected with sill made of prefabricated reinforced concrete slabs, combined with the tight pre-quaternary clay core. There is an asphalt-paved road on the damn crest [9, 17].

The thermal monitoring system for the Kozłowa Góra dam was designed by Krzysztof Radzicki from Cracow University of Technology and developed by Neostrain Sp. z o.o. This fully automatic system of quasi-3D monitoring (continuous over the length of the dam and extended in chosen piezometric cross-sections) was described in detail by Radzicki et. al [16]. Temperature sensors in piezometric cross-sections, the measurements from which are discussed here, are mounted along the entire length of each piezometer at 1 meter intervals (Fig. 2), thus enabling measurements of vertical temperature profiles in the dam body. On the upstream and downstream slopes of each instrumented piezometric cross-section, numerous temperature sensors are mounted for measuring external thermal loads.

3. Thermal monitoring of earth dams

Thermal monitoring is used to detect and assess seepage and erosion processes on the basis of analysis of temperature measurements in earth dams. The methodology is intensely developed by some major research centers in the world, and in Poland by the Institute of Water Engineering and Management at the Cracow University of Technology.

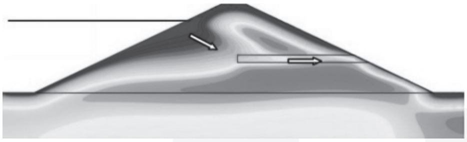
Thermal methods of analysis of water flow in the ground are based on the relation in the heat and liquid transfer processes, which are coupled. These relations are described by the energy conservation equation. At zero water velocity, only heat is transferred, which is a relatively slow process. However, even only a change of soil moisture due to even minimal leakage causes local changes in the thermal front transition rate and disturbs the local isotherm pattern [4, 11]. In the event of the liquid's movement, heat is also transported with the mass of water also. This process is called advection and is predominant over conduction. Heat and water (seepage, leakage) penetrate the facility's body and cause significant disturbance in the temperature field; the greater the disturbance, the higher the seepage rate.

As a result, the body temperature measurements and their analysis allow to identify leaks and to monitor seepage processes. Since the erosion process changes the structure and values of soil parameters, it affects the values and directions of water flow vectors in the seepage area, and, consequently, influences the soil medium temperature field. Each type of erosion process causes characteristic disturbances of the hydro-thermal field, allowing its thermal monitoring exploration [4, 13, 14]. In summary, the thermal monitoring method enables the detection and analysis of the seepage and erosion processes. As an example, Fig. 3 shows the numerical analysis of the impact of the development of erosion processes, such as suffosion, on the thermal field in the dam section, at the same thermal and hydraulic loads. It can be seen that the effect of water temperature from reservoir on the thermal field inside the dam's body is predominant where the hydraulic gradient is the largest, and the impact increases with the development of erosion processes.

a)

The dam without internal erosion

b)

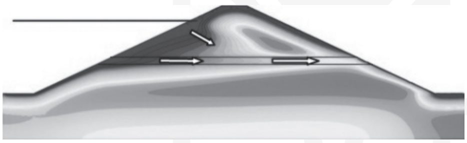


Suffosion layer developed up to mid-section;
suffosion layer permeability coefficient
K = 1e-4 ms-1

c)

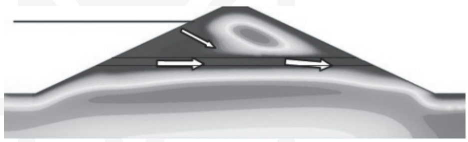
Suffosion layer developed up to mid-section;
suffosion layer permeability coefficient
K = 1e-3 ms-1

d)



Suffosion layer covers the entire section;
suffosion layer permeability coefficient
K = 1e-4 ms-1

d)



Suffosion layer covers the entire section;
suffosion layer permeability coefficient
K = 1e-3 ms-1

Fig. 3. Thermal fields of an earth dam cross-section at the same point in time for various suffosion layer lengths and the layer's permeability coefficient (Radzicki, Bonelli, 2012) [14]

4. Hypothetical seepage/erosion mechanisms in earth dam body and foundation

As mentioned in the introduction, a number of seepage/ erosion phenomena have been monitored on the main dam. The multi-year monitoring shows that one of the areas where significantly intense erosion and seepage processes have been observed is the section between and around piezometric cross-sections 6 and 7, of total width ca. 200 m. Benchmarks located on the facility crest within this region showed subsidence therein by ca. 2 cm in the last 20 years, including an increase in its intensity between 1995 and 1998, when the settlement amounted to 1 cm. In addition, over a few hundred meters of the downstream bench along the dam's right side, the bench crest has lowered by several tens of centimeters. Soil compaction probing carried out from the bench on the downstream side of the dam showed that, at the seepage curve level in the bench embankment, the soil compaction in most of the holes was described as loose and very loose in a ca. 0.3 to 0.6 m thick layer. Beneath, in the foundation under the bench, the soil is mid-compacted [19]. In the zone of piezometric cross-sections 6 and 7, some voids and cracks were observed in the stone paving on the upstream slope that could indicate the locations of enhanced seepage penetration into the body. In addition, relatively large rates of delivery from drainage wells and moisture on the downstream bench surface were observed in this zone. Variability analyses of the position of piezometric levels in the frontal dam, in particular at the reservoir water level increase during the 2010 flood, indicate in several dam sections, including this piezometric cross-section 6, a likely unsealing of the clay core in its top part [9, 17, 18]. Two hypotheses were defined of the mechanism of the seepage/erosion processes in the main dam body, under the assumption that the may be concurrent. The first hypothesis, substantiated with observations of the relationship of changes in the piezometric levels relative to the reservoir level, and with geo-engineering tests of the dam body, assumes that the clay core in its upper part above elevation 277.80 m OSL does not provide an effective anti-seepage protection, as evidenced by the piezometric water levels measurements, whereby at the reservoir's damming above the aforementioned value, the pressure very considerable increases. In addition, the upper part of the core is above the freezing zone. Freezing of waterproof elements of earth dams made of clays affects the emergence of horizontal fractures and a potential significant increase in the rate of seepage. Many years of impoundment, prior to 2006 above elevation of 277.80 m OSL could result in the development of a privileged seepage path between the upper porous part of the core towards the bottom toe in the facility body. The other hypothesis assumes the development of suffosion processes in the dam's tertiary foundation resulting from the sheet piles' underdepth and/or leaks. The sheet piles' partition in the river valley most likely has not reached the impervious formations in the valley bottom and is suspended in the Pleistocene complex of sandy-gravel formations filling the river valley. This applies particularly to the right part of the dam (piezometric cross-sections 4-4 to 7-7). Also doubtful may seem the tightness of the wooden sheet piles itself, set in the foundation, after more than 70-years of operation.

The low damming level maintained at the dam in 2014 prevented the first hypothesis' verification and analysis by the thermal method. In contrast, a multi-scenario analysis of the second hypothesis was possible and included permeability coefficient estimate in the lower and saturated part of the embankment and in the foundation, the results of which are shown in the following two sections hereof.

5. Matching the numerical model of dam's thermo-hydraulic cross-section to measurements

Mapped in the numerical model was the frontal main cross-section 6-6. For the modelling, a FeFlow model was used, whose accuracy and calibration in this regard has been verified by numerous applications and checks against models and physical objects [6]. A numerical model of the cross-section was developed, under the assumption of transient heat transfer and variable water levels on the upstream side, based on actual multi-point temperature measurements on the upstream and downstream slopes, and water level measurements in the reservoir. In the next step, by applying the back-analysis method, (1) the dam body and foundation permeability coefficients were matched to reference-literature parameters pre-established for the soil types identified by way of geo-engineering tests, (2) the seepage window opening under the wooden sheet piles was determined. While fitting the model, the best correlation was sought of the modelled piezometric level and, in particular, of the modelled vertical thermal profiles measured in piezometers for cross-section 6 in the analyzed period, with actual measurements. Fig. 4 shows a comparison of the actual and modelled temperatures in the vertical profiles in piezometers 6C and 6D. The mean error between the data obtained from thermal monitoring and modelling amounted to 0.66°C for piezometer 6D and 0.46°C for piezometer 6C. The maximum error for piezometric pressures was 0.18 m for piezometer 6D and 0.10 m for piezometer 6C. Finally, the modelling allowed to determine the permeability coefficient for the foundation as 1e-5 m-1s, and the seepage window opening under the sheet piles as 0.3 m.

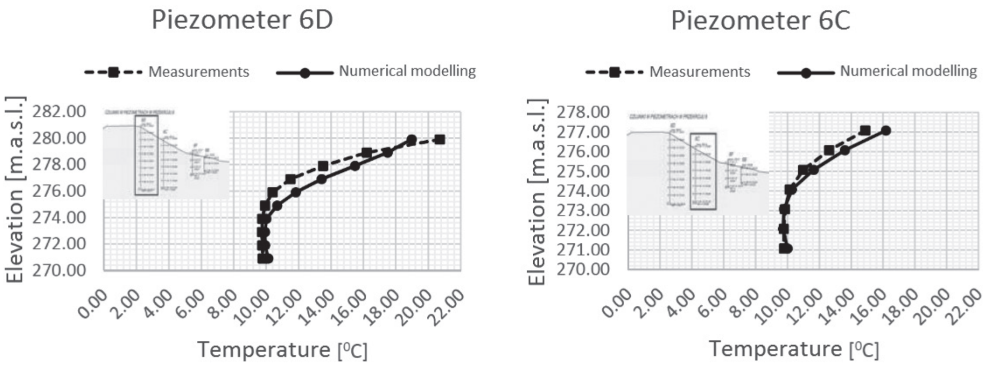


Fig. 4. Vertical thermal profiles in piezometers 6D and 6C for data obtained from the numerical model and data from thermal monitoring of the Kozłowa Góra dam on 30 June 2014

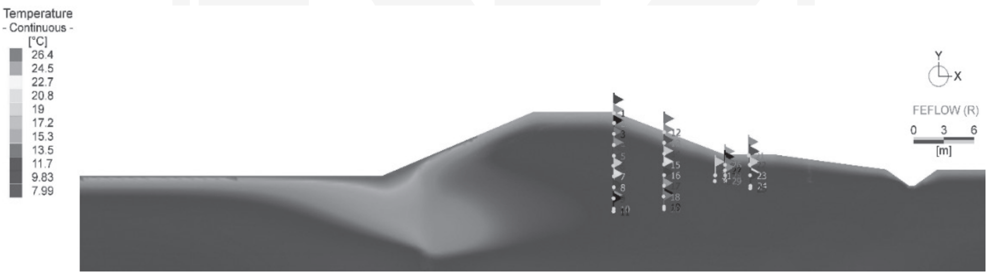


Fig. 5. Thermal field of Kozłowa Góra dam cross-section 6-6 modelled for 30 June 2014

The obtained data do not completely rule out the occurrence of suffosion erosion processes in the dam foundation, but they ruled out the existence of severe erosion or a zone of particularly privileged flow and locally severe erosion. Hypothetical impact of the emergence of such a zone on temperature measurements is presented in section 6.

6. Modelling the hypothesis of seepage/erosion processes occurrence in the foundation

This section describes the hypothetical impact of a privileged flow zone with deteriorated soil parameters on the temperature field in cross-section 6-6, if such a zone existed in the foundation. In relation to the calibrated numerical model described in section 5, the permeability coefficient in the foundation was increased by an order of magnitude, i.e. to *k* = 1e-4 m-1s. There was a seepage opening between sheet piles and impermeable tertiary foundation layer as in the previous case. Fig. 6 shows the modelled vertical temperature profiles in piezometers 6C and 6DZ with actual measurements. A significant increase in the difference between modeled and the actual temperatures is evident from elevation of 275.50 m OSL downwards, increasing with depth in relation to the results

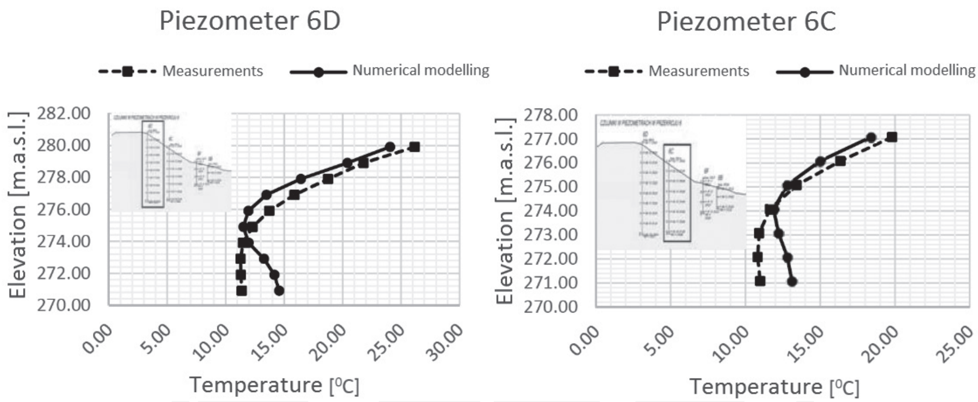


Fig. 6. Thermal profiles in piezometers 6D and 6C for data obtained from the numerical model and data from thermal monitoring of the Kozłowa Góra dam on 4 August 2014

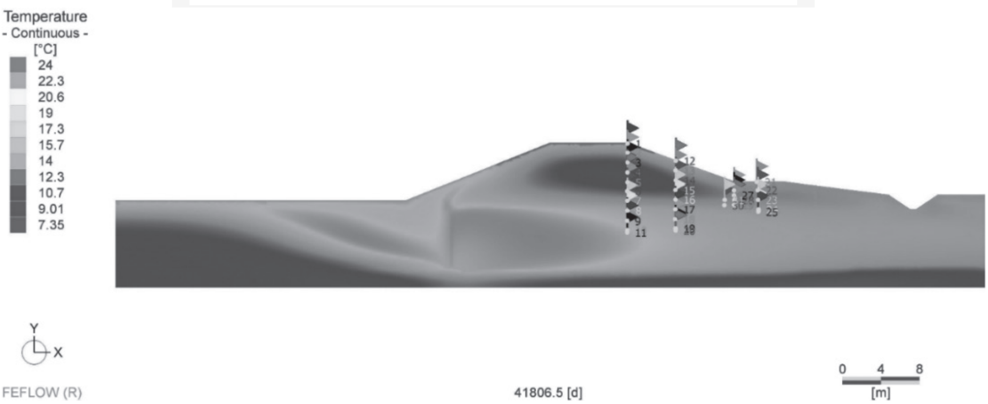


Fig. 7. Thermal field of Kozłowa Góra dam cross-section 6-6 modelled for 4 August 2014

shown in Fig. 4. Such a thermal anomaly would result from the modelled, hypothetical zone of privileged flow, and consequently the increased advective heat transfer towards the downstream side.

7. Summary and conclusions

Based on the temperature measurements at the Kozłowa Góra dam and thermal-hydraulic numerical modelling, the hypothesis of potentially intensified seepage/erosion processes in the dam foundation was verified and rejected. The seepage opening between sheet piles and the impermeable tertiary foundation layer was also confirmed, which, however, does not result in significant intensification of seepage/erosion processes in the dam foundation as far as the present case is considered. The modelling confirms the thermal method's high sensitivity to seepage rate changes, which enables detailed analysis of the seepage field and accurate adjustment of the soil permeability coefficient using the back-analysis method. Unfortunately, due to the low reservoir water levels in the analyzed period, the hypothesis of fractured upper part of the core could not be analyzed by the thermal method.

Thermal monitoring methods, together with advanced data analysis, are well suitable for the analysis of complex problems of water seepage through earth dams. The Kozłowa Góra dam is provided with an advanced thermal monitoring system that allows a wide range of analyses, the results of which will be presented in future papers. However, the application of that particular method in view of cross-sectional analysis with an already existing piezometric cross-section does not require a permanent system of temperature measurement system at the dam. In addition, installing temperature sensors, e.g. rented for several months (length of the period depends on, inter alia, the size of the dam and its body and foundation soil parameters) would be sufficient.

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