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APPLICATION OF THE ELECTRICAL IMPEDANCE SPECTROMETRY METHOD FOR MONITORING FILTRATION PHENOMENA ON THE EXAMPLE OF KAROLINKA EARTH DAM

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ABSTRACT

The paper presents the results of monitoring electrical properties of the soil of the body of the earth-fill dam of the Karolinka water reservoir in the fourth year after its reconstruction ended. Monitoring was carried out using the Z-meter device applying the electric impedance spectrometry method with the focus on seepage through the earth-fill dam of the water reservoir. Information about the changes that occurred in the dam body before and after the implementation of the measure (the construction of a cut-off wall when the dam was reconstructed in 2013) was obtained by monitoring the changes of the electrical resistances of the soil of the dam with time.

Key words: earth-fill dam, seepage, remediation, monitoring, electrical impedance spectrometry

INTRODUCTION

The Karolinka dam and water reservoir (VD), (see: Fig. 1) belongs to the administration of Povodí Moravy, s.p. (PM, Morava River Basin Agency), Horní Morava Plant, Valašské Meziříčí Shop.

The monitoring of changes that took place in the soil of the dam using the electrical impedance spectrometry method (EIS) was commenced in March 2011 (Pařílková et al. 2011, Rupp 2011). Karolinka VD has been operated with a lowered water level on the reservoir practically since its first fill-up, because of seepage observed on the downstream side of the dam. That was the reason why the monitoring was started. The monitoring using the EIS method with a frequency of once a month continues also in 2017 and is carried out by the project E!7614 in the EUREKA programme. In the Czech Republic the main participant of this programme is the GEO*test*, a.s. company. The EIS method belongs to the methods and procedures, the common aim of which are activities in the area of the stability and safety of the operation of earth-fill dams of water reservoirs (Hodák 2010–2012).

The Karolinka VD is located on the Stanovnice water stream at the 0.75 km of the river above the town of Karolinka in the Vsetin District. The main purposes of the VD are the use of water for the group water system Vsetin – Vlara, protection from floods, preservation of the minimum discharge in the water stream below the dam and generation of hydroelectric energy. The total volume of the reservoir is 7.644 mil. m^3 and the area of the basin is 23.1 km^2. The VD was built from 1977 to 1985, the reconstruction of the VD was carried out in 2013, including the additional sealing of the core of the dam, which was designed using a conventional underground cut-off wall from self-hardening cement-bentonite suspension (www.pmo.cz).

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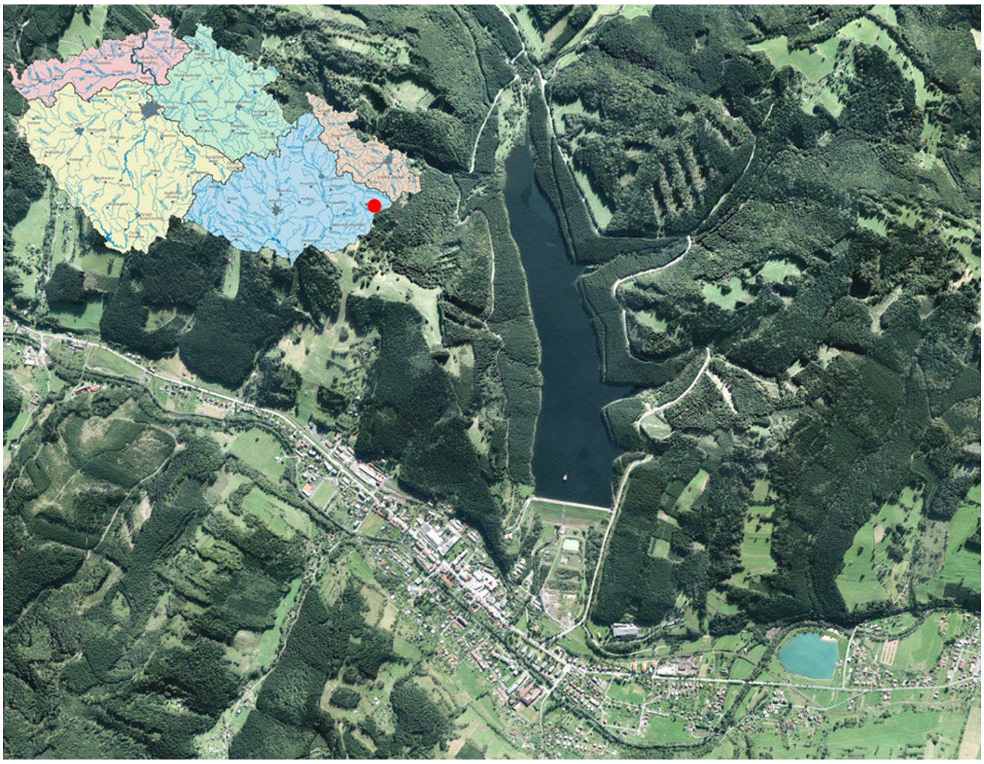

Fig. 1. Location of water reservoir Karolinka VD (www.mapy.cz)

Earth-fill embankment dam of the Karolinka VD

The dam of the Karolinka water reservoir was constructed as a straight (on the ground-plan), zoned earth-fill embankment dam made of local gravel materials with a vertical loamy central core connected to a grouting tunnel. The height of the dam above the base of the foundation is 47 m and the length of the dam crest is 391.5 m. The slope of the upstream face is 1 : 3.3 – 3.6 and of the downstream face 1 : 2.2 – 2.4. The downstream face is divided by two berms at the levels 500.00 m a.s.l. and 511.60 m a.s.l. The dam crest is at the level 522.70 m a.s.l. The material of the dam is deposited in the individual zones so that the core is surrounded from both sides by filters of gravel extracted in the valley of the Stanovnice water stream (www.pmo.cz). The face zones are formed by gravel sand from Novy Hrozenkov. The upstream face is fortified with macadam filled with bitumen. The downstream part of the base of the foundation and the stabilizing downstream zone of the dam are drained by sheet drains 0.6 m thick (www.pmo.cz, Jareš and Krejčí 2015, Silová 2015). A longitudinal section through the dam, displaying a newly constructed underground wall, is shown in Figure 2 (Jareš and Krejčí 2014).

According to the Regulation No. 471/2001 Coll. of the Ministry of Agriculture (MZe) on dam safety supervision, Karolinka VD has been included in the II Category. The frequency of dam safety inspections during the permanent operation of the dam and reservoir is once in 2 years. The administrator of the Karolinka VD – PM – ensures the implementation of dam safety supervision (TBD) in permanent operation through an authorised organisation of the MZe, the company VODNÍ DÍLA - TBD a.s. (VD TBD). All periodical measurements and monitoring are carried out by attendants and an authorised person according to the Programme of Dam Safety Supervision, compiled in compliance with Regulation 471/2001 (Zapletalová 2016), in which an overview of monitored processes is prescribed by Annex No. 2. The required monitoring of processes indicating dif-

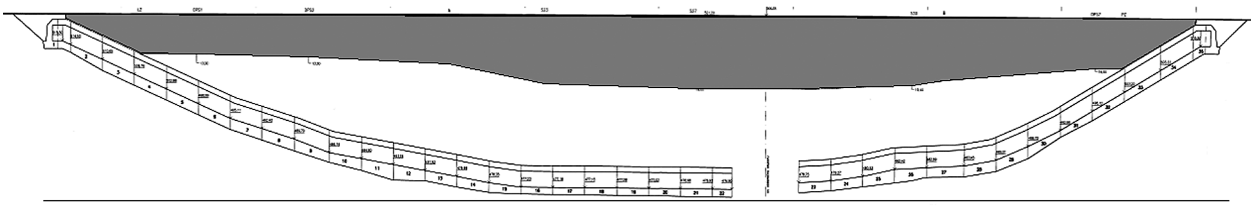

Fig. 2. A longitudinal section through the earth-fill dam of the Karolinka VD with a newly constructed wall (Jareš and Krejčí 2014)

ferent types of potential failures is focused on the following areas:
- operating conditions,
- weather conditions,
- the seepage regime,
- deformations.

Within the programme of TBD, three evaluating limits are determined, namely the limit of vigilance, limit values and critical values. Possible types of dam failure are specified as:
- slip of the upstream/downstream part of the dam with disturbed static or dynamic stability of the dam and its base,
- internal erosion of the dam or its base,
- surficial erosion of the dam by overtopping,
- failure of safety and discharge facilities.

The first fill-up of the reservoir revealed inrush areas with a different intensity of seepage on the downstream face of the dam, which they have not been eliminated with full satisfaction despite all of the measures made. So, attention to the monitoring of the seepage regime using the EIS method was given.

Since the fill-up of the water reservoir in February 1986, when the water in the reservoir reached a level of 517.61 m a.s.l., i.e. 2.39 m below the edge of the emergency spillway, inrushes of water have occurred on the downstream face, with a different intensity of seepage. Investigations proved that seepage was caused by the insufficient permeability of Hrozenkov gravel sand forming a zone in the downstream face of the dam and by technological indiscipline while filling the individual layers. The layers of the stabilization zone of the downstream face were filled using very heterogeneous materials that differ particularly by the content of silt particles, which should have been less than 4% according to the project, but in reality the content of silt particles reached up to 11% (Jareš and Krejčí 2015). The seeping water flowed from certain layers of the face zone onto the downstream face of the dam where wetted places occurred (see: Fig. 3). After seepage was discovered on the downstream face of the dam, work was commenced, focused on the clarification of the origin of the seepage water and dealing with its effect on the safety of the VD. In addition, it included proposals and provided remediation of the VD (Woznica 1993, 1998, Bláha et al. 2003, Rupp 2011, Hájek 2011, Macík 2011, Rupp and Pazdírek 2012, Jareš and Krejčí 2015).

Investigations in 2004 and 2010 were already carried out for the reason of the planned construction of a cut-off wall. A wide range of soil grain sizes was confirmed (from fine-grained soils – CH, CS, CG to gravelly soils – GM, G-F), as well as a different composition of mixed soils (similarity was not even found between boreholes close to one another), causes diverse permeability of the core and of the downstream stabilising parts in the horizontal and vertical directions. Beds of gravelly soils were determined in the area of the core, reaching a depth of around 10–12 m (510.00 m a.s.l.) and 17–18 m (about 505.00 m a.s.l.). It was proved that the boundary of the better-quality soils of the core was encountered at the depth of about 12–13 m below the crest (509.00–510.00 m a.s.l.). It was equally re-verified by an investigation carried out in 2010 that the crest of the core is in reality by about 0.8 m lower than described in the project documentation (the level of the crest of the core locally varies and lies about 1.5 m below the dam crest, i.e. at the maximum level of the water surface in the reservoir) (Zapletalová 2016).

Based on the presented conclusions it was stated that the in homogeneity of the core material would in all likelihood manifest in the entire length of the

Fig. 3. Karolinka VD – seepage on the downstream face of the dam (archival photographs by PM and VD TBD)

dam. At the end of the investigation in 2004 it was already recommended that the construction of a cut-off should be considered along the entire length of the dam because all findings had shown a potential risk to the filtration stability during the extreme stages of the water level in the reservoir. The Pöyry Environment a.s. Company (today AQUATIS, a.s.) prepared project documentation for the work contractor – EUROVIA CS, a.s. to carry out the construction. The additional sealing of the core of the dam was designed using a conventional underground cut-off wall from self-hardening cement-bentonite suspension. In order to obatain a building permit a change of the design of the additional sealing of the dam was made – according to the documentation of the work implementation (DPS) it was proposed to seal it using jet grouting. The cut-off wall was constructed in 2013. The technical parameters according to the DPS are as follows:

- the length of the cut-off wall – 352.25 m (including jet grouting in the keying, 2 × 25 m long),
- the depth of the cut-off wall is variable in a section of the dug wall between 10.50 m and 19.30 m; the depth of the wall in a section of jet grouting is between 1.0 m and 11.0 m,
- the width of the cut-off wall – 0.60 m,
- the width of the pavement – 3.5 m.

MONITORING OF THE SEEPAGE REGIME

In the dam and downstream areas below the dam, several types of geotechnical monitoring work have been carried out to this day, focused on the monitoring of seepage. Particularly the development and trend of the following elements have been monitored:

- the pressure of water in the basement,
- the pressure of water in the dam body,
- moisture content of the core,
- seepage on the downstream face of the dam,
- seepage at the base of the dam,
- total seepage.

The monitoring system includes also the monitoring of seepage flowing to the grouting tunnel and the measurements of pore pressures (see: Fig. 4). It consists of 4 core boreholes drilled into the dam core and fitted with vibrating wire piezometers of the PK45A type with integrated thermometers (manufactured by SISGEO Srl – Italy) at the levels 13.0 m and 20.0 m for the long-term monitoring of pore pressures and temperatures (Rupp and Pazdírek 2012).

The method of electrical impedance spectrometry

In March 2011, 4 rods were installed into the downstream part of the earth-fill core of the dam, monitoring changes in the electrical conductance of soil using the EIS method, thus indirectly monitoring changes in its moisture content (Fejfarová 2014). EIS is an indirect method of measurement, using the frequency relationship between electrical impedance characteristics to analyse the properties of soils (Pařílková 2010). The EIS method is designed for monitoring the processes governed by change in electrical conductance of soils caused, e.g., by change in the content of water or its electrical properties (e.g. monitoring of moisture content in soils), by electrokinetic processes on a boundary (e.g. electrode-soil grain, soil grain-soil grain of a different structure), or for documenting the basic visualisations of an inter-component boundary (e.g. electrode × water).

The monitoring of the Karolinka VD earth-fill dam is carried out by 4 probes installed in the locations of predicted anomalies, each with 22 sensors fitted at the levels of assumed anomalies. The placing of probes (see: Fig. 5), their total length of 13 m, the length of measuring electrodes of 0.05 m and the position of sensors on the probe – irregular division (Pařílková et al. 2011) were based on the location of observed inrushes of water (Woznica 1993), the knowledge of the characteristics of used materials (Čištín and Hálek 1975) and the technical documentation of the dam construction. Because the probe VL_1 was damaged beyond repair during dam reconstruction in June 2013, it was necessary to install a new probe identical with the original one (carried out in September 2013).

In relation to the characteristics of the soil, monitoring is carried out at the frequency f = 8,000 Hz with a period of switching between measurements t = 0.100 s and the number of repetitions on one sensor n = 5. A three-terminal connection of electrodes is used on the probe, which requires the application of an adapter (Radkovský 2011, 2012).

Changes that take place in the dam soil are monitored through electrical variables based on the principle of the method of measurement (Pařílková 2010). The real component (the electrical resistance R) and the imaginary component (the reactance X – apparent electrical resistance) of the electrical impedance **Z** are measured separately

$$\boldsymbol{Z} = R + jX \tag{1}$$

or the admittance

$$\boldsymbol{Y} = \frac{1}{\boldsymbol{Z}} = G + jB \tag{2}$$

where **Y** is admittance, G is electrical conductance, and B is susceptance (Berka 2010). Each of the evaluated variables describes a process that takes place in soil and that has a dominant effect on its value.

Monitoring that is carried out regularly once a month using Z-meter devices was supplemented until the year 2014 by measurement at exceptional situations – a higher intensity or frequency of precipitation (rain, snow), an increase/decrease of the water level in the reservoir, frost, etc. on the contrary, in the year 2017 6 measurements through sustainability of project E!7614 were planned. The pattern of the continuously monitored climatic variables and the altitude of the water level in the reservoir with time are given in Figure 6.

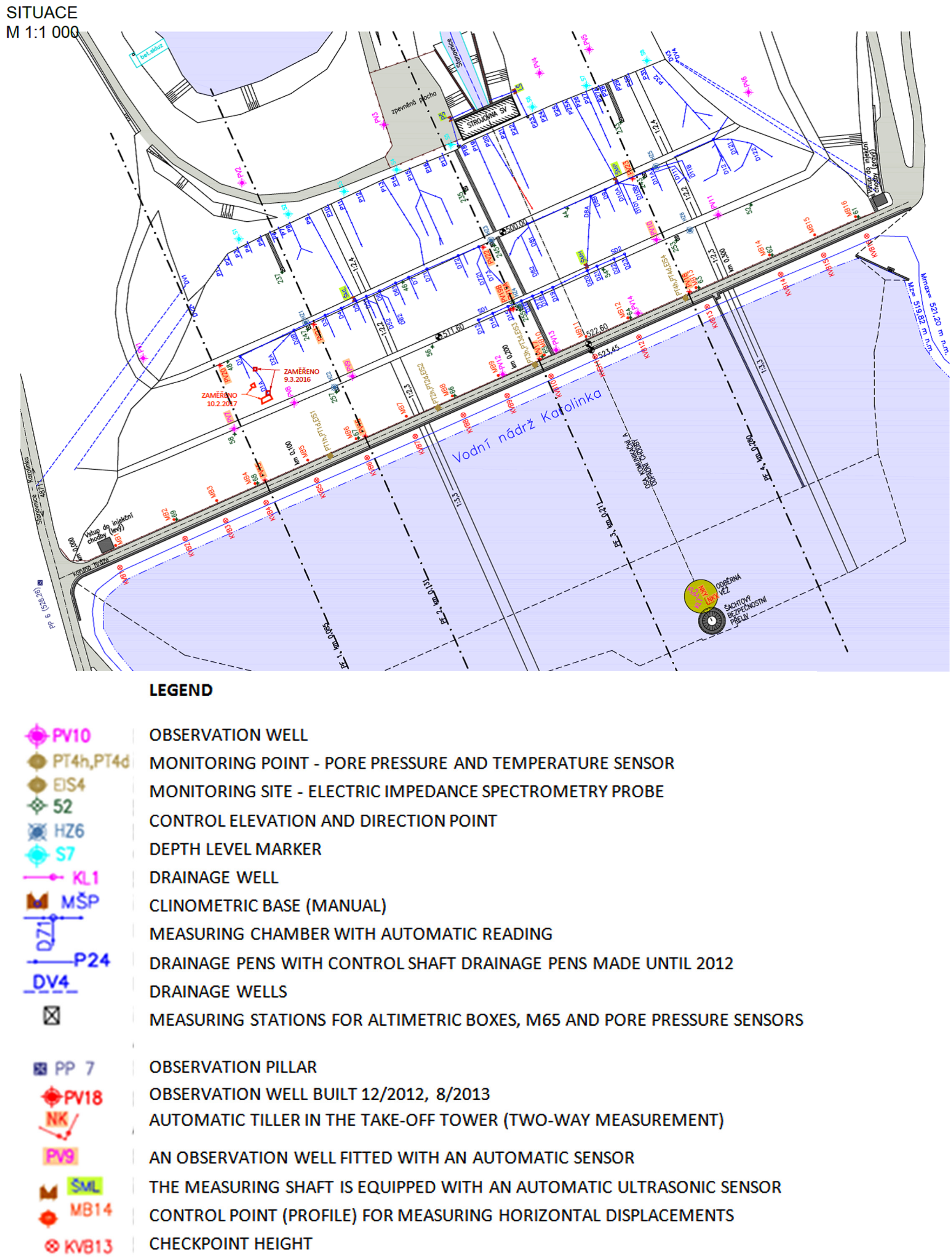

Fig. 4. Karolinka VD – the system of monitoring (Pařílková et al. 2017)

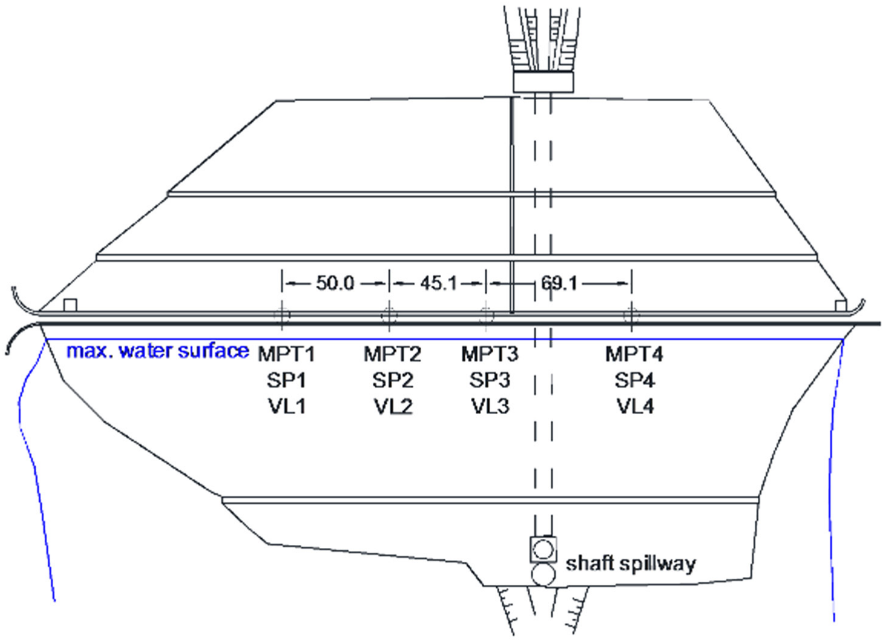

Fig. 5. Karolinka VD – situation of mounted probes EIS (Pařílková et al. 2016b)

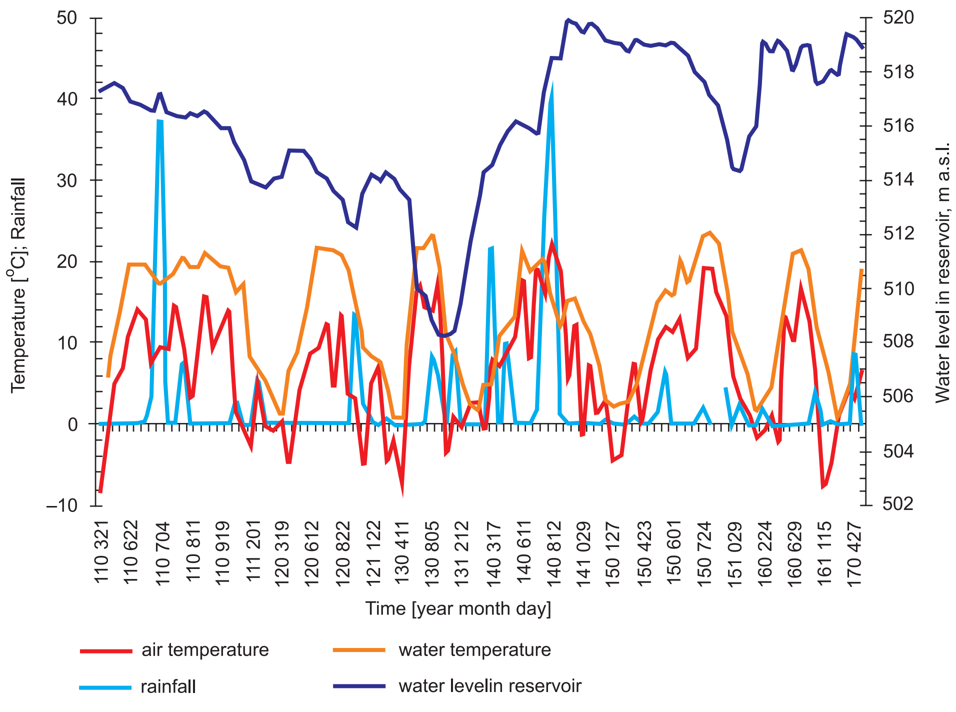

Fig. 6. Monitored variables with time

EVALUATION OF MONITORING

One of the ways of evaluating monitoring is, for example, the maps of electrical conductance *G* of the soils, depending on the height *h* with relation to the top of the dam (processed in the Surfer 8 program), indicating the places with increased water content in the monitored section of the earth dam (see: Fig. 7). The first EIS electrode is at h = –1 m (1 m under the top of the dam), the last electrode is mounted at a height of –13 m, the sealing wall was installed between March and October 2013. All maps are, for the

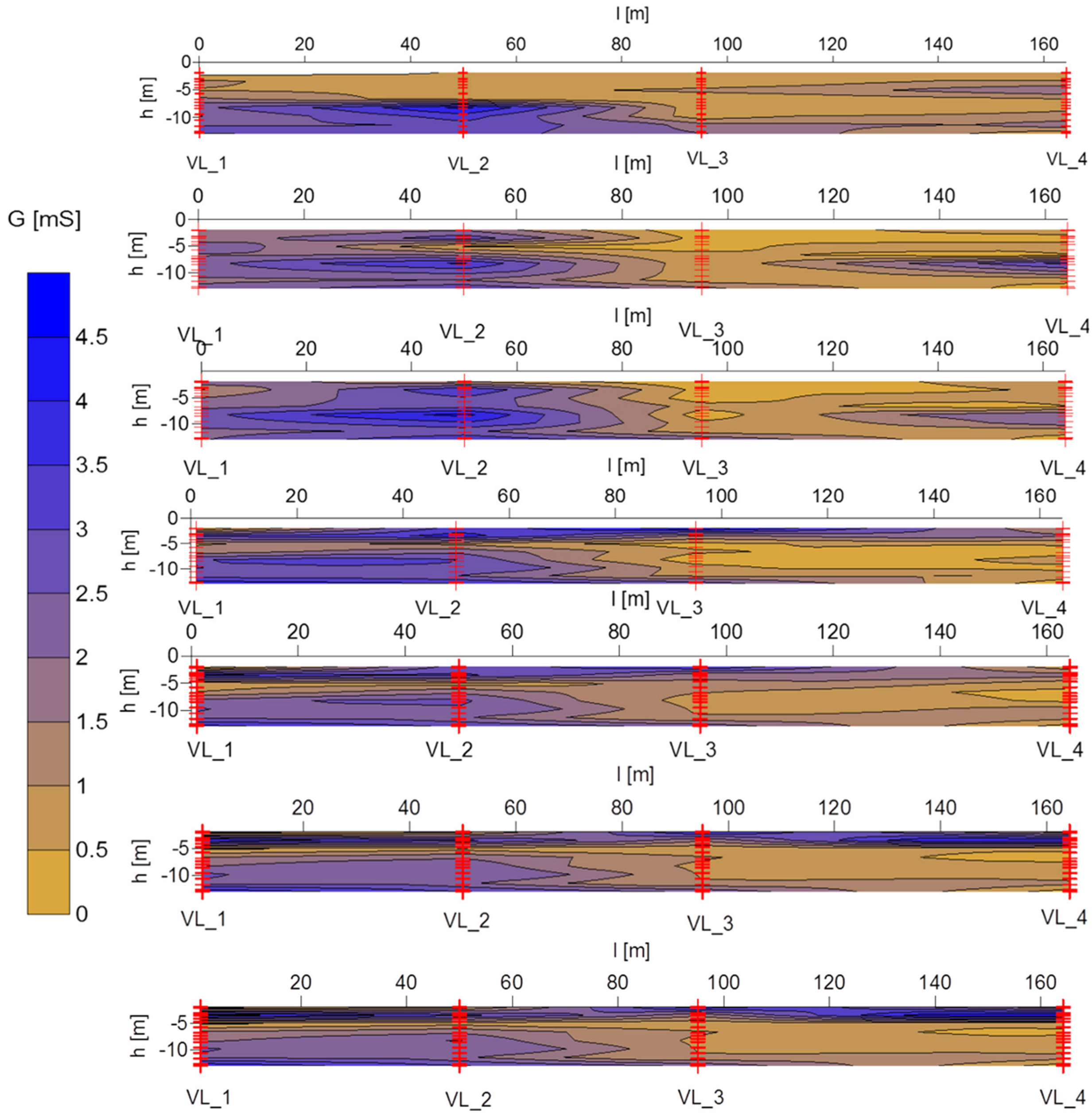

Fig. 7. Maps of the electrical conductance of the soil of the monitored section of the earth-fill dam for the month of March, 2011 to 2017 (sorted successively)

sake of comparability, evaluated for a uniform range of electrical conductivity. The blue color represents the high water content of the soil, the brown color means the soil is relatively dry.

Based on the results of measurement it can be stated that the measured *G* values reach extremes after reconstruction essentially at the same height level as before reconstruction. However, after reconstruction, the higher *G* values are reached at higher water levels in the reservoir. In February 2015, January 2016 and February 2017, at the downstream face of the dam in the profile between the VL_1 and VL_2 probes i.e., in the left part of the dam between the upper and lower berms, seepages appeared (see: Fig. 8 and 9). The visual observations and the above statement are evidenced by increased electrical conductance values at –10.6 m and –12.9 m monitored by the monitoring EIS apparatus (see: Fig. 10).

Fig. 8. Observed seepages in February 2015, January 2016 (photo by J. Pařílková)

Fig. 9. Observed seepages in February 2017 (photo by Burdíková)

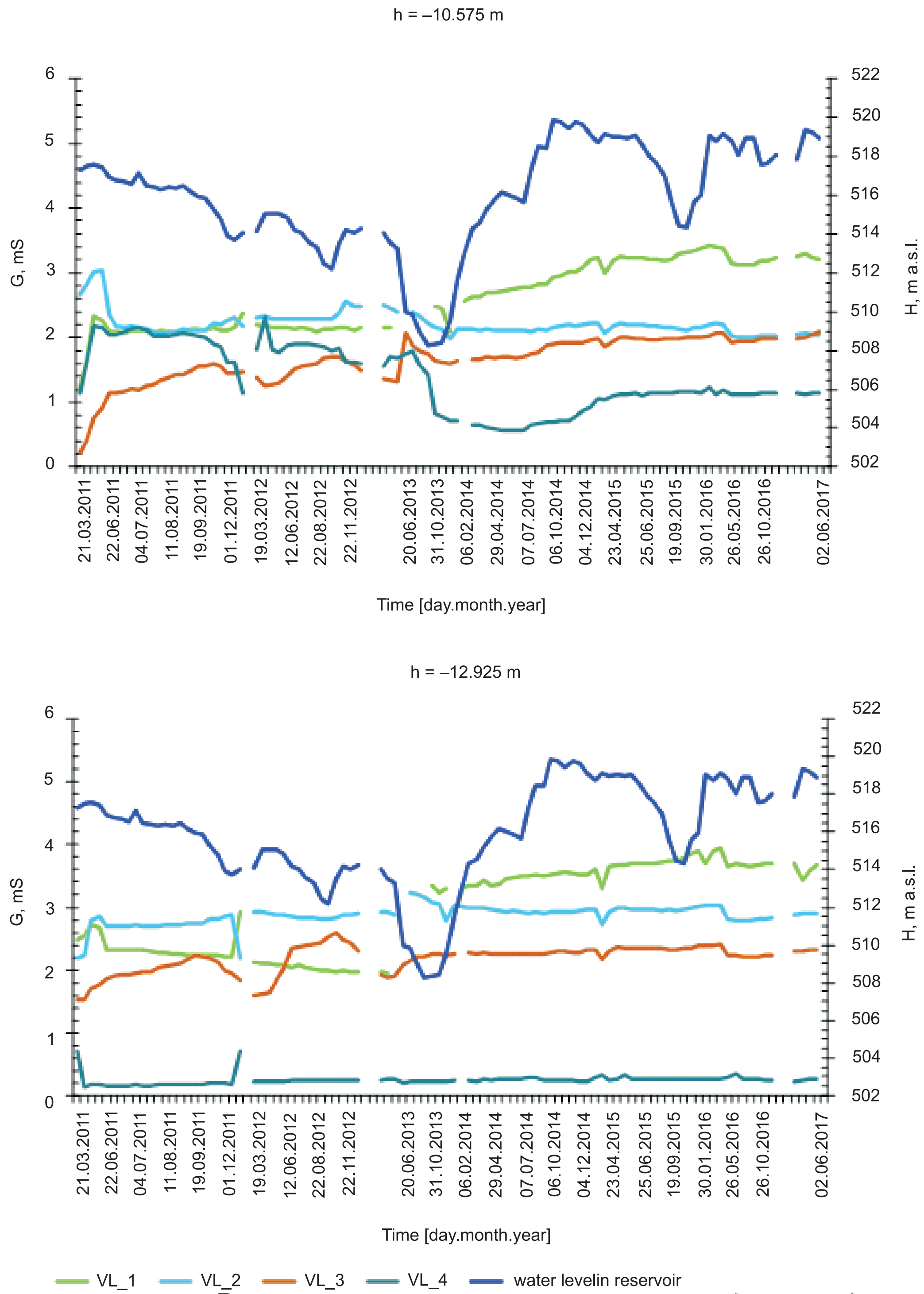

Fig. 10. The course of electrical conductivity of the soil at selected levels and the water level in the reservoir between 2011 and 2017

The conclusions above are supported by the evaluation of the total average admittance $\bar{Y}$, determined as an inverse value of electrical impedance, for each probe (see: Fig. 11), expressed as the arithmetic average of the measured values of electrical impedance on all of the 20 sensors of one probe. It is necessary to emphasise that the given method of evaluation suppresses the extremes identified by each probe, but the variable takes into account both the change in water content in the soil and the change in its structure. The evaluation of the trend of the development of $\bar{Y}$ determined by each probe in relation to the changes in the water level in the reservoir after the dam reconstruction has proved that there is no direct link between these parameters (Pařílková et al. 2016a).

After analysing the time pattern of the values of the total average admittance, it can be stated that the most

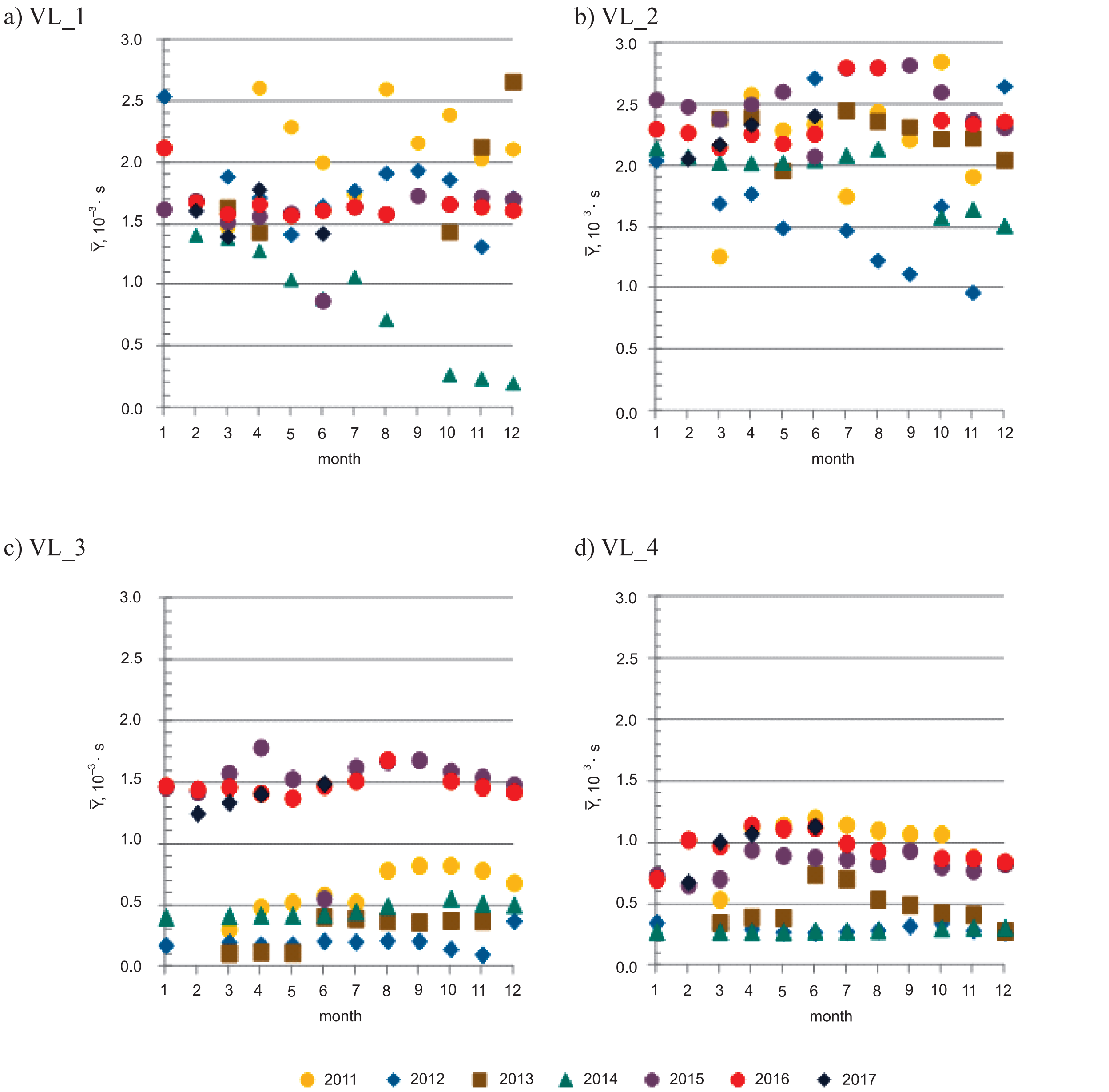

Fig. 11. Time pattern of total average values of admittance for each EIS probe from 2011 to 2017

significant quantitative change in the values of $\bar{Y}$ was recorded by probe VL_3 in 2015 and the trend is also kept in 2016 and 2017. Whereas in 2014 it is possible to state that the values on probes VL_2 to VL_4 were stable during the year (on probe VL_1 even with a distinctly diminishing trend corresponding to the decrease in water content in the soil), in 2015, 2016 and in the measured months of 2017 this does not hold true. The values of $\bar{Y}$ on probes VL_2 and VL_4 in 2016 and 2017 are at the level measured in 2011. All probes recorded the same or higher values than in 2012, i.e. before the installation of the cut-off wall. The decreasing pattern of the values of $\bar{Y}$ in 2014 with an increase of the water level in the reservoir simultaneously with an approximately 40% decrease of the values of $\bar{Y}$ relative to the same months in 2012 would evoke a high efficiency of seepage prevention made by the cut-off wall, but the facts from the years 2015 and 2016 do not support this theory (Fránková 2015), which was also documented by the data in the measured months of 2017. Higher values of $\bar{Y}$ are still shown on probe VL_2. They demonstrate that the content of water in its surroundings is probably by about 20% higher as compared to the year 2012 in the months from September to February; the trend is slightly diminishing and related to weather conditions. An inrush of water has been observed around probe VL_2 which was remediated in May 2016 and the seepage is monitored. Nevertheless, a new seepage area was targeted in February 2017 (see: Fig. 4). Higher values $\bar{Y}$ also occur between 2015 and 2017 on the VL_3 probe.

CONCLUSION

It was stated that water leaks through earth-fill embankment is significant technical problem of the Karolinka VD dam. A number of technical measures have been carried out to identify their origin, which consisted, for example, in the separation of rain and leakage water at the engine room under the dam. The anticipated seepage path from the upstream face to the sealing core is likely to be dependent on how the transport and compaction of sealing core materials took place. The soils used for the construction of the dyke have a wide range of grain sizes, the possible cause of the seepage paths is the non-observance of technological procedures and the use of inappropriate materials. The manager of the work – the Morava River Basin, in 2013, took a major step in asking for a public works contract for the complete supply of the building called "VD Karolinka – Reconstruction of the earth-fill dam". As part of the implementation of the public contract, a sealing wall was built in the upper part of the sealing core of the dam. The water reservoir could have been additionally filled up to the useful water level only in October 2014.

In sum, it can be said that in the area of the largest seepage, at a height of –5 m to –10 m between probes VL_1 and VL_2, the values of electrical conductance of soil has been significantly reduced after the reconstruction, and thus the degree of water saturation of pores has probably decreased as well. A similar conclusion can also be drawn for the given range of heights in case of probe VL_4. In this respect it is possible to describe the application of the cut-off wall as efficient.

When studying the patterns of electrical conductance measured by probe VL_1, it is evident that the area of the higher degree of water saturation of soil pores has shifted lower, approximately to a height of –10 m to –11 m (the cut-off wall has a variable length from –10.50 m to –19.30 m). After the reconstruction, VL_1 probe was located in a part of the dam closest proximity of the cut-off wall at about –11 m, and water probably flows under the wall, which is also documented by the numerical model. Although the value of the newly formed extremum is lower than the value of the higher-located one from 2012, it is however necessary to point out that it is steadily slightly increasing during the year. In the other probes, which are located in the zone of a larger distance from of the cut-off wall, at approximately –19 m, this area of a significant increase of the values of electrical conductance and thus of the increased degree of water saturation of soil pores does not occur, which is also supported by the decreased value of the measured total seepage. A partial increase of G relative to the year 2012 can also be observed in the lowest levels of measurement in VL_4 probe, here however the extremum is not so visible and its value fluctuates during the year. When considering the results of measurement and their method of interpretation, it is possible to state that the depth of the constructed cut-off wall in the area of VL_1 probe is insufficient. This conclusion is also supported by the fact that in February 2015 as well as in January 2016 an inrush area re-appeared approximately in the zone of the original historical inrush of water (where snow melted). The situation that had arisen was solved by conveying seepage down to the new drain in May 2016, but the cause of the inrush of water has not yet been satisfactorily identified. The cause can be, e.g., the water flowing on the slope or precipitation water can pass through the drainage mat or the water may come from the reservoir, then flow underneath the cut-off wall and subsequently pass through the drainage mat; but this may also concern the combination of both these causes. It is however necessary to consider also a scenario with a failure of the cut-off wall.

It is also necessary to draw attention to the increase of the values of electrical conductance in the area of about –2 m to –4 m beneath the dam crest, which is the most significant on probe VL_3; it can be partially observed on the other probes as well.

The complexity of the construction of the earth-fill dam of the Karolinka water reservoir and of the ongoing processes shows that assessment only on the basis of monitoring by the EIS method is not clear, but it gives a certain idea about the changes in the water saturation of soil in the monitored area of the dam. It will be necessary to determine in the overall concept of the efficiency of the implemented measures how the given fact correlates with seepage measured in the base of the dam and other monitored parameters such as the water level in the reservoir, the temperature of water and soil, the pattern of pore pressures, etc. The technology of construction and the process of ageing of the clay-cement mix of the cut-off wall will certainly have an important effect.

All of the given conclusions are based on the assumption that neither the mechanical nor the chemical characteristics of the monitored soil have been changed by the installation of the cut-off wall, and the changes in the values of electrical variables are dominantly a consequence of change in the degree of water saturation of soil pores.

The monitoring by EIS apparatus and the obtained results have helped to identify local anomalies in the dam body and have supported a requirement for their remediation. The dam is still observed and regularly monitored, but the existing system of measurement and monitoring has not yet been capable of satisfactorily indicating where the water inrush comes from.

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ZASTOSOWANIE METODY EIS DO MONITORINGU ZJAWISK FILTRACYJNYCH NA PRZYKŁADZIE ZAPORY ZIEMNEJ KAROLINKA (CZECHY)

ABSTRAKT

W artykule przedstawiono wyniki monitoringu właściwości elektrycznych korpusu zapory ziemnej zbiornika wodnego Karolinka po czterech latach od jej modernizacji. Monitoring przeprowadzono przy wykorzystaniu aparatu Z-meter stosując metodę spektrometrii impedancyjnej, skupiając się na przeciekach przez zaporę. Informacje o zmianach, które miały miejsce w korpusie zapory przed i po wykonaniu przesłony filtracyjnej (budowa ściany szczelinowej w 2013 r.) uzyskano na podstawie monitorowania zmian oporów elektrycznych gruntów korpusu.

Słowa kluczowe: zapora ziemna, przesączanie, remediacja, monitoring, spektrometria impedancyjna